Multistorey Frame System for Energy Efficient Buildings

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ABSTRACT

A combination of concrete and timber elements can lead to advantageous structural and environmental solutions. Especially in the case of multi-storey buildings concrete floor structures could significantly improve acoustic and fire safety building performance and at the same time they can ensure horizontally rigid floor structures from the perspective of spatial rigidity. Subtle HPC precast frame thus represents effective alternative to timber-based framework by providing possibility to build higher buildings, while allowing the other structures to be based on wood. Technical parameters of HPC structural frame and environmental qualities connected with the higher use of renewable materials can result in construction of multi-storey energy efficient buildings.

Results of long-term research project and development of a new optimized precast construction system based on high performance concrete is presented. The system is particularly aimed for building construction in passive or zero-energy standard. High performance concrete used for the superstructure enables lowering of concrete consumption up to 50 - 70%. Developed structural concepts have been proved by theoretical and experimental results. The paper presents in more detail a construction of the experimental RC frame and a LCA study of developed subtle HPC frame, which is compared with standard solution.

Keywords: *high performance concrete, precast frame, wooden envelope*

1. INTRODUCTION

Nowadays, there is an increasing tendency to build multistory wooden based buildings usually from CLT (cross laminated timber) panels or using timber frames. However, there are limitations in a space rigidity of multistory timber structures, in acoustic performance of timber floor structures and in a fire safety. The combination of light concrete frame with concrete floor structure and wooden based other parts of structure (envelope, partitions, roof structure) could solve some of these problems. Significant advantages of subtle elements are material and energy savings during production, transport, manipulation and construction on building site. Accumulative properties of RC structures can contribute to thermal stability of buildings indoor environment. This will mainly help buildings that need cooling in summer. On the other hand, concrete frame provides stronger load bearing structure in comparison to timber structure. In the same time such composite structures will be more resilient and better prepared for extreme situations in a changing environment.

Figure 1 presents a concept of concrete subtle frame for construction of houses in passive energy standard. The concept is based on a combination of subtle load bearing HPC frame with building envelope and other parts like partitions, roof structure etc. mainly from wood or other biobased materials.

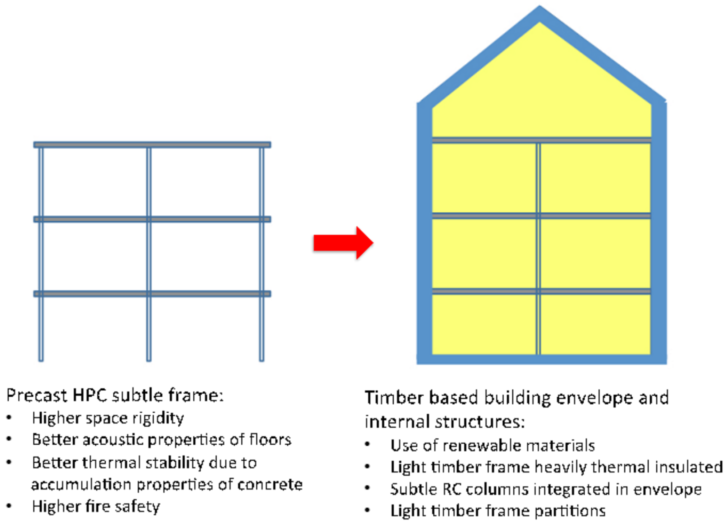

Figure 1: Concept of structural system for multi-storey energy efficient buildings from precast HPC frame and timber based other structural parts

Developed structural frame from high performance concrete (HPC) is aimed for 2 to 6-storey residential and civil buildings (health and social care, education, temporary housing, administration). The combination of timber and concrete can enhance utilization of renewable structural materials also for construction of larger buildings. Concrete floor structures offer advantages in comparison with whole timber structures in the field of acoustics, fire safety, accumulation of thermal energy and spatial rigidity.

2. CONCEPT OF EXPERIMENTAL OSEEB RC FRAME

Experimental structure has been built within the third year of the research project TA03010501: "Optimized subtle frame for energy effective buildings" (OSEEB). The aim of the project was to develop a universal and variable load bearing structure for energy efficient buildings that meets the criteria of sustainable development. The concept of load bearing structure is based on a subtle HPC precast system. The principal aim was to minimize the amount of used material by lightening of the structure using shape optimization of structural elements from high performance concrete. Because of lower self weight of the lighter structure a load on footing bottom, demand on transport and consequent environmental impacts are decreased. Ground plan of the experimental load bearing frame is apparent from Figure 2.

Structural details of the OSEEB system are designed to minimize thermal bridges and to enable maximal variability of ground plan, structural height and full height etc.

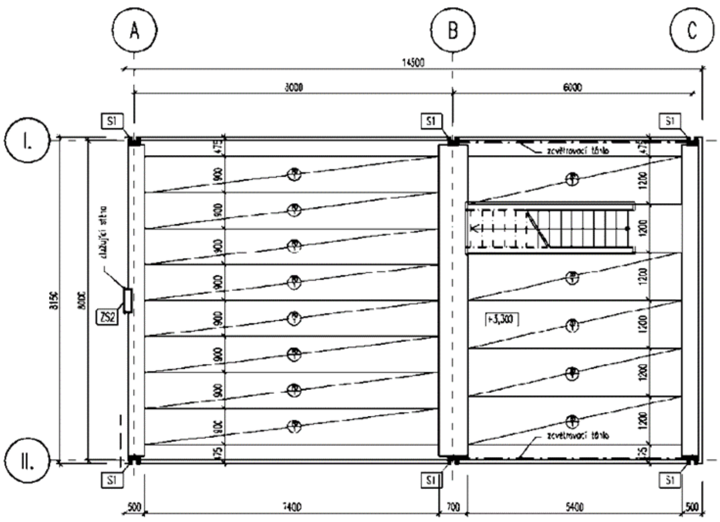

Figure 2: Ground plan of the experimental OSEEB frame

Implementation of experimental frame should show technological consequences and will enable testing of individual structural components on real structure. Structural elements are slab girders and floor panels, subtle multi storey columns, and foundations structural elements – precast pocket footings (alternatively from recycled concrete) and foundation sills. Development of the structural components was accomplished within previous years of the research project. Optimization process resulted in final shapes of cross sections, methods of lightening of structural elements and their mutual connection systems. Experimental structure will be also used for monitoring of structural performance under the long term load.

2.1 Description of experimental OSEEB frame structure

Precast experimental OSEEB frame is designed as two storeys, basementless structure with ground plans dimensions of 8.15 x 14.5m with pitched roof from timber beams. Maximal height of the ridge is 9.3m above the terrain level, the structural height of the 1st floor is 3.8m, the structural height of the 2nd floor is 2.9m and the height of the attic is 2.9m.

Load bearing structure has two bays with axial columns distance of 8 x 8m and 8 x 6m. Main vertical load bearing elements are two storeys C shaped columns from high performance fibre concrete with cross section of 180 x 250mm; main horizontal load bearing elements are prestressed slab girders with notches for embedding of floor panels. Girders and floor panels have equal height of 300 mm in order to create flat soffit and free plan in larger spanned floor structures. Floor panels are lightened by lightening elements from secondary raw materials (recycled material Stered), alternatively from light weight building materials (liapor concrete). Floor panels are from HPC with standard reinforcement or prestressed. For larger spans there is the option of cross fastening of floor slab by post tensioning method. Cables for post tensioning are anchored into side girders. HPC columns are designed from concrete class FC70/85, steel B500B, alternatively B550B, girders, bracings and floor panels from concrete class minimally FC60/75 reinforced by tensioned cables Y1860S7 with diameter of 15.7mm and reinforcement B500B. Columns are embedded into footings from recycled concrete with dimensions of 1.8 x 1.8m and 2.0 x 2.0m and height of 1.05m. Girders are connected to columns by Peikko corbels, longitudinal side beams (bracings) are mounted on girders notch and connected by shear spikes in order to ensure horizontal rigidity of individual components connections.

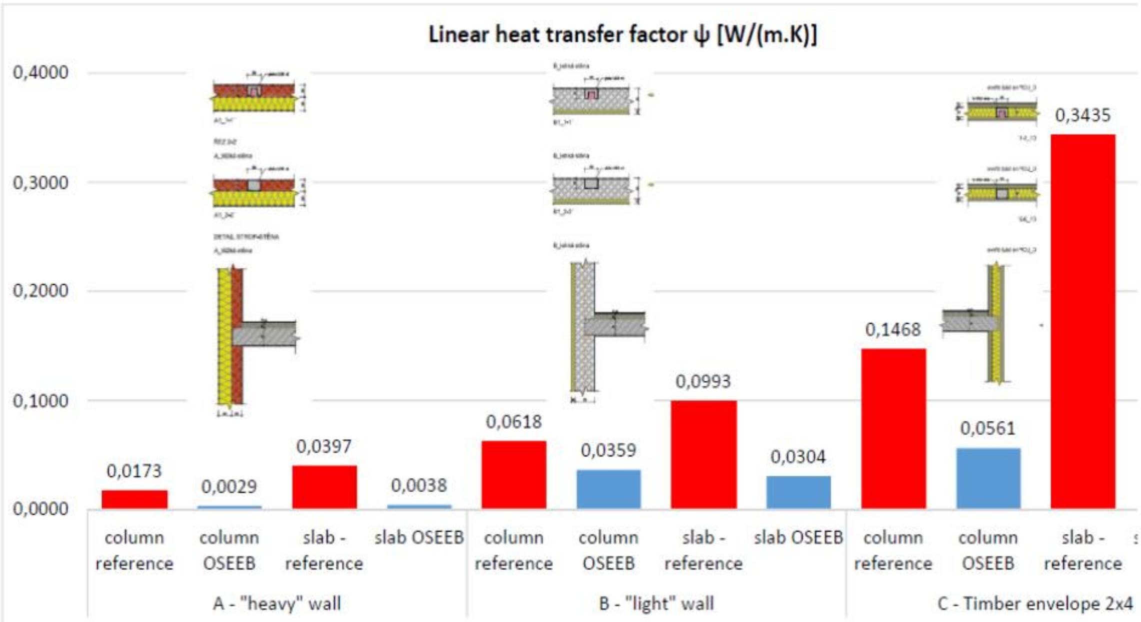

Figure 3: Comparison of linear heat transfer factor ψ for assessed variants of building envelope

2.2 Energy optimization of buildings using OSEEB

The aim of building energy optimization of OSEEB was to eliminate risks of thermal bridges, to minimize heat transfer of main structural parts placed in the building envelope and structural solution enabling continuous layer for air tight and water vapour barrier. Following structural details have been optimized: (i) Columns in the building envelope, (ii) Horizontal beams and slab, (iii) Column footing. Three material variants of building envelope as ceramic blocs with ETICS, foamed concrete with ETICS and timber building envelope based on 2 x 4 system have been taken into account. All variants were designed for the same thermal performance of U = 0.15 W/m^{2}K meeting requirements for low energy and passive buildings in the Czech conditions.

Linear heat transfer factor ψ [W/m.K] was determined according to Czech standards for selected structural variants and compared to common design and size of columns (300 x 300mm) and beams (250 x 700mm). Minimal columns cross-sections and flat horizontal beams of the same height as the slab enable integration into building envelope and minimizing of thermal bridges. Inner side of the column in the part designed as “C” profile is filled with thermal insulation, which again helps to reduce thermal bridges. The results of optimization and comparison to common solution are shown in Figure 3. Significant reduction of thermal bridges is obvious.

3. CONSTRUCTION OF EXPERIMENTAL OSEEB FRAME

Experimental structure OSEEB – Optimized subtle frame for energy effective buildings – was built in UCEEB (University Centre for Energy Efficient Building, CTU in Prague) in Bustehrad area. Precast structural elements of OSEEB frame were produced in company ŽPSV at the end of the year 2015. The company AZS 98 provided precast pocket footings and foundation sills from recycled concrete and company Peikko delivered connecting corbels. The erection of frame started after land remediation by placing the precast pocket footings in February 2016 (Figure 2), installation of above-ground parts of the structure took place during March and April 2016, see Figure 4 to 9. Firstly, subtle two-storey columns were assembled followed by stiffening wall and foundation sills (Figure 5). Subsequently, flat girders and longitudinal stiffeners were fitted to columns by Peikko´s corbels (Figure 6). After temporary securing of girders against torsion, the floor panels were installed - prestressed elements per module 8m and non-prestressed panels per module 6m. (Figure 8).

Figure 4: Precast pocket footing

Figure 5: Assembling of subtle columns, stiffening wall and foundation sills

Figure 6: Structure of the 1st floor

Figure 7: Assembling of transverse bracing on girder fitted on Peikko´s corbel

Figure 8: Structure of experimental frame with unfinished ceiling above 2nd floor

Figure 9: Finished load bearing structure of experimental OSEEB frame

Peripheral girders at ceiling levels provide rigidity of the frame in longitudinal and transverse direction. Girders are connected to columns by Peikko corbels and by shear spikes in order to ensure force transmission in the plane of the ceiling from all load combinations. After assembling of floor structures, the shear spikes and joints between panels and girders were sealed by concrete grout SikaGrout. Experimental OSEEB frame structure was finished in April 2016 (Figure 9). In the first stage, the both floor structures were implemented as laterally non-prestressed, followed by a first static load test. After performing load test, the floor structure of the span 8 x 8m above 2nd floor was additionally prestressed and static load test was repeated.

4. LIFE CYCLE ASSESSEMENT OF SUBTLE FRAME

A set of environmental information data on concrete components and related processes has been collected and determined within the research performed at the Faculty of Civil Engineering, Department of Building Structures of the Czech Technical University in Prague. These data are based on regionally available materials and are based on source data provided by companies producing and/or selling their products mainly on the Czech market. The data have been stored and organized in CONCRETE LCA$^{Tool\ 3.0\ CZ}$.

A simple two-storey experimental building with a ground plan of 8.15 x 14.5m was chosen for life cycle analysis (LCA) study covering environmental assessment and comparison of two selected concrete frame structure alternatives (Figure 2 and 9). The house is designed with a very universal layout enabling design of many feasible structural and material alternatives.

4.1. Description of concrete frame structures alternatives

The complex (LCA) was performed for two various RC frame structures that were designed for afore mentioned building. This analysis focuses primarily on load-bearing structures and does not cover building envelope, partitions and surface finishes. The analysis covers transport of the raw material to the prefa plant, concrete production, transport of prefabricated elements to the building site, demolition and deposition of the concrete at the end of the structures lifespan. The RC frame structure's alternatives are as follows:

- V1 reference precast RC frame structure from concrete C30/37 and C40/50 with columns dimensions of 400 x 400mm, girders 550 x 650mm, stiffeners 190 x 600 mm and hollow core prestressed panels with thickness of 265 mm.
- V2 subtle HPC frame structure from concrete HPC70/85 with subtle columns as shown in Figure 6, girders dimensions of 500 x 300mm, 700 x 300mm, stiffeners 470 x 300mm and floor structure panels as described in chapter 2.1. HPC for floor panels and columns is reinforced by dispersed steel fibers (1% vol.).

4.2. Inventory of input data and LCA results

In the following analysis the expected life span of frame structures was considered for all alternatives equally 100 years. Construction life phase covers: amount of used concrete (precast elements), amount of individual components needed for concrete production, amount of the reinforcement divided according to a type of reinforcement and related transport to construction site. End of life phase calculates with the amount of waste from demolition, amount of demountable components that can be reused and related transport.

Aggregated impact data for specific life cycle phases construction are presented for primary raw materials consumption and primary energy consumption in Figure 10. It is evident that environmental impacts in the construction phase are significantly higher in comparison with end of life phase. In Figure 10 shows the influence of individual components such as cement, aggregate, water, admixtures etc. on primary energy consumption. It is apparent that main environmental impact is due to cement and steel reinforcement. Transport, construction process, aggregates and admixtures cause minor effect.

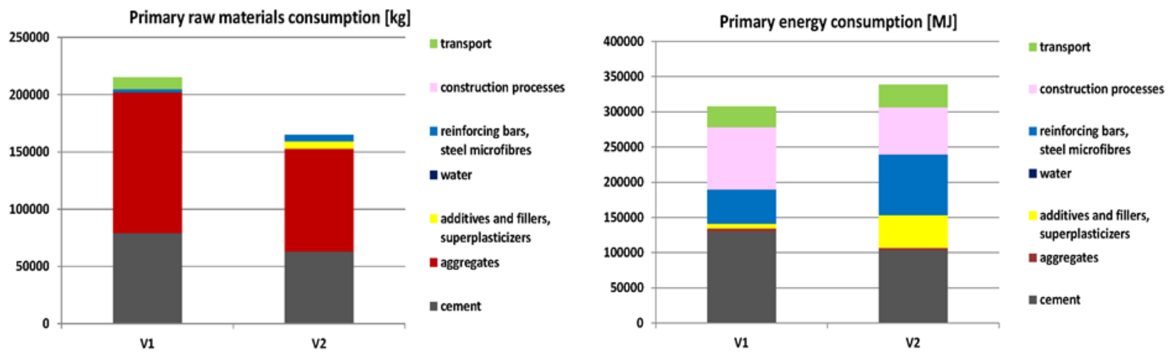

Figure 10: Aggregated data - Primary raw materials and primary energy consumption

Figure 11 presents the final comparison of assessed alternatives. 100% is represented by V1 (precast RC frame structure from C30/37 and C40/50). The environmental values of both variants of frame are comparable in primary energy consumption and emissions criteria. In total 20% of raw material consumption and 11% water consumption can be saved by utilizing V2 alternative, structure as optimized subtle HPC frame.

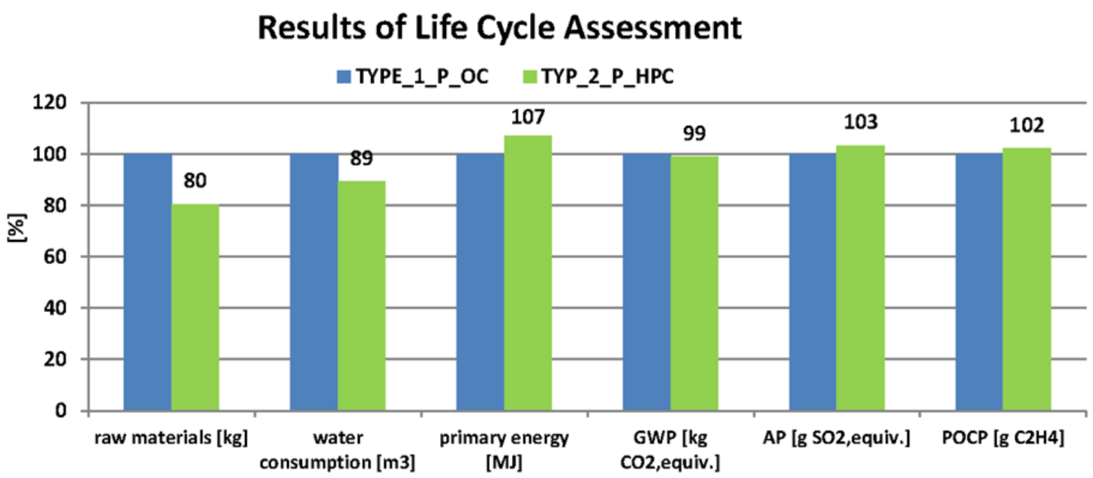

Figure 11: Aggregated data of assessed variants frame (GWP – Global warming potential, AP – Acidification potential, POCP – Photochemical ozone creation potential)

5. CONCLUSION

Two alternatives of RC frame structures have been analysed and compared. The results of analysis proved expectation that subtle HPC frame structure is the environmental friendly alternative from two assessed alternatives. The results show that the high quality of mechanical and environmental performance of new silicate composites creates the potential for wider application of High Performance Concrete in building construction in the future. The further advantage of subtle HPC frame can appear in areas with regulated size of built-up area (e.g. in dense inhabited town areas). With higher demands on thermal insulation parameters of building envelopes increases also their thickness. The possible integration of subtle columns in building envelope can thus save valued inner space. The construction of an experimental frame validates the feasibility of the project and production technology of elements and installation of frame structure.

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