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Harmonization of Structural and Functional Lifespans of Prefabricated Residential Buildings

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ABSTRACT

Technological developments and social trends can create demand for new building functionalities, necessitating the adaptation of existing buildings. This paper presents the development of a modular building structural system that provides for the harmonization between the structural and functional lifespans of a building in order to achieve greater sustainability. The limitations of the existing prefabricated urban buildings with respect to their adaptability are contrasted with the proposed solution. The use of prefabricated engineered materials, such as cross laminated timber (CLT) and CLT-concrete composites, in conjunction with a modular system, reduces any climatic effects. The inherent advantages of incorporating detachable connections allows for the necessary structural adaptability, subsequently harmonizing and elongating the structural and functional lifespans. The resulting sustainable concept, when applied to residential buildings, could serve as a solution to address projections of future urban growth.

1. INTRODUCTION

Over the years, numerous general sustainability models have been proposed to reduce global environmental concerns. These models all require sustainable buildings. A model that can be applied to architecture consists of three subsystems (sets) denoting the economy, environment, and society, with their intersection representing the sustainable domain [1]. Sustainability can only be accomplished if the architectural concept is analyzed according to its impact on these three subsystems. Such an analysis applies to all phases of the building's lifecycle: construction, service, and demolition. From a sustainability point of view, of these three phases, the building's service lifetime is of critical importance.

Life cycle assessments, an accepted and effective method to analyze environmental impacts [2], show that extended building lifespan contributes to reduced climatic effects [3]. Buildings have several components, such as their structure, infill, envelope and services, each of whose life spans are based not only on their material lifespan, but also on their functional performance [4].

The positive contribution of adaptable buildings towards achieving sustainability was evidenced in terms of economic, environmental and social considerations [5, 6].

The design process must consider the functional and aesthetic adaptability, in conjunction with structural modifiability [7]. Each of these components have their own lifespans. For buildings, it is essential to identify the relationship between the functional and structural lifespans [8]. The main difficulties are that functional lifespans are getting shorter and shorter, which further increases the demand for building adaptability for specific uses. However, structures are usually not designed to enable adaptation of that frequency.

One difficulty of the design is allowing for the adaptability of the building structure. In this research, a modular system is developed, intended primarily for residential applications, which uses steel, cross laminated timber (CLT), and CLT-concrete composite prefabricated materials to allow for a detachable connection design.

2. PREFABRICATED BUILDINGS

Economic objectives have played an important role in the concept development for many existing buildings. [9]. Standardization, in most areas, including the construction industry, has led to economical solutions. In 1924, Mies van der Rohe wrote [10]: "I consider the industrialization of building methods the key problem of the day for architects and builders. Once we succeed in this, our social, economic, technical and even artistic problems will be easy to solve." Le Corbusier, Gropius, and Wachmann, laid down the bases of prefabrication. Building on these ideas, Kieran and Timberlake [11] provide high quality and lasting solutions for prefabricated buildings. Such structural systems are based on high tolerance members with standardized connections that ensure quality. The small base-units of the structure allow for free mass forms and space configurations within the static framework.

Today, the question is no longer whether a multi-criteria optimized, sustainable pre-fabricated building is designable [12], but whether it is possible to create individualized living spaces using the developments in prefabrication, thus providing an answer to changing housing needs.

In Hungary, since the 1960s, building factories have produced structural members for "panel buildings" in Hungary, drawing on Soviet and Danish examples, see Figure 1. The most important criteria in the technical design of the "panel" buildings was the unification and the introduction of norms that improved the efficiency of construction [13]. An important consequence was the increase of buildings' capacities (size and number of units). During the 1960s and 1970s, these "panel" factories reached an annual output of up to 30,000 living units.

Figure 1. "Panel" urban residential buildings in Hungary (www.fortepan.hu: VÁTI, 1972.)

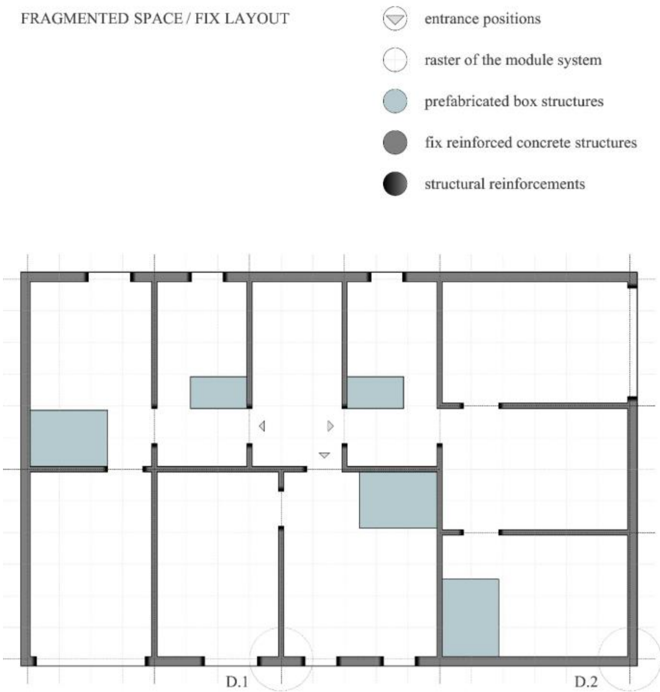
The load bearing structure of the "panel" buildings has the height of a storey and generally consists of room-sized wall elements; for shorter spans, room-sized slab elements, and for longer spans, divided slab elements. These elements are interconnected along the edges with in-situ cast concrete, creating the desired spatial system. The buildings are stiffened in two directions by 15 cm thick walls, since the stiffness of the slab-to-wall connections is limited. The structural system initially used a 30 cm, and later a 90 cm base system with 2.7 m, 3.6 m, and 5.4 m spans. Due to existing norms, the span of the buildings and the flexibility of the floor plans could not be increased [14].

3. ADAPTABILITY OF PREFABRICATED "PANEL" BUILDINGS

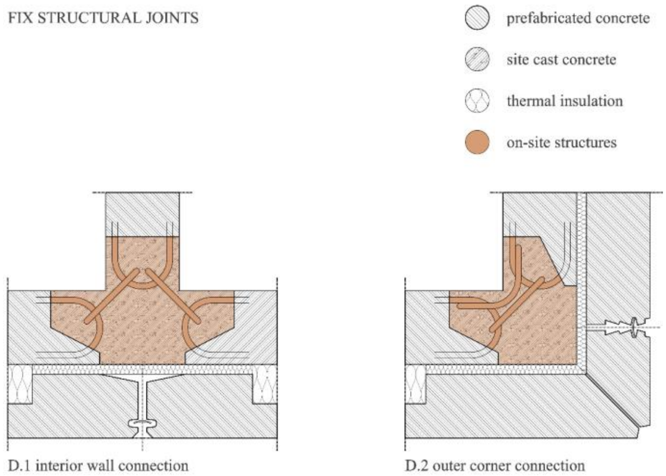
Although the expected structural lifespan of the "panel" buildings exceeded 100 years, they became functionally obsolete within 30 years of service. The small transverse size of the panel buildings significantly limited the quality of achievable spaces and, due to the solid-wall system (see Figure 2), only provided for a limited number of living space configurations. Thus, these buildings must be modified in order to fulfill new functional demands.

Topological modifications require structural analysis and lead to invasive construction processes. Therefore, most modifications must be limited to improving the comfort level by means of technical upgrades and interior design.

In certain cases, the living spaces can be changed by fully or partially relocating partition walls. The main limiting factors are the inner structures and the building mechanical systems. Fixed structural elements within the inner space significantly reduce the modifiability of the building.



(a) Layout of a "panel" building



(b) Details of a "panel" building

Figure 2. Typical layout and details of a "panel" building

While the structural defects of the "panel" buildings are mostly construction related, as a result of the factory-controlled prefabrication technology, the quality of the reinforced concrete members is usually adequate. The defects due to the on-site assembly process are observed at the interconnections of the prefabricated members. The steel bars extending out from the "panel" elements are welded together and then cast into concrete. Typically, the thermal insulation and the welds of the interconnected "panel" elements were discontinuous, or the cast contained gaps, causing thermal and structural hazards. Overall, the faults of the "panel" buildings stemmed from the connection design, the adopted construction technology, and the material selection. Therefore, any new design must avoid such problems, as is consistent with the solution presented in this paper.

4. RESULTING NEW PREFABRICATED BUILDING

The fixed structural elements appearing in the "panel" building's living spaces, as described earlier, reduced the functional lifespan by creating a fragmented space, and were built with materials and technologies that could only be modified with structural alterations. In contrast, the proposed building concept is based on an open space model, according to the modular system described. Based on the above, no fixed structural members were placed in the living spaces limiting these members exclusively to the outer part of the structure. In these peripheral locations, fixed structures do not pose a problem, since these members are expected to stay in their initial configuration during the entire lifetime of the structure. Within the fixed outer shell exists the 5.40 m x 28.5 m adaptable space, as shown in Figure 3, which includes the actual living unit spaces.

The built environment, including newly designed residential buildings, should fully satisfy individual preferences [15], for factors such as temperature, humidity, audio, and light effects, etc., which depend on context and personality type. Therefore, flexible and variable functional layouts should be created, and the building structure should be able to incorporate various layouts [16, 17]. Ideally, it should also allow for future renovations.

The design concept above creates a living zone that is flexible, adaptable, and within which living units can be configured side-by-side and the space can be divided with replaceable elements. Since these space delimiting elements (mobile walls, furniture) are attached with demountable connections, any modification can be accommodated. This solution increases the functional lifetime of the building without any alteration done to the load bearing structural system.

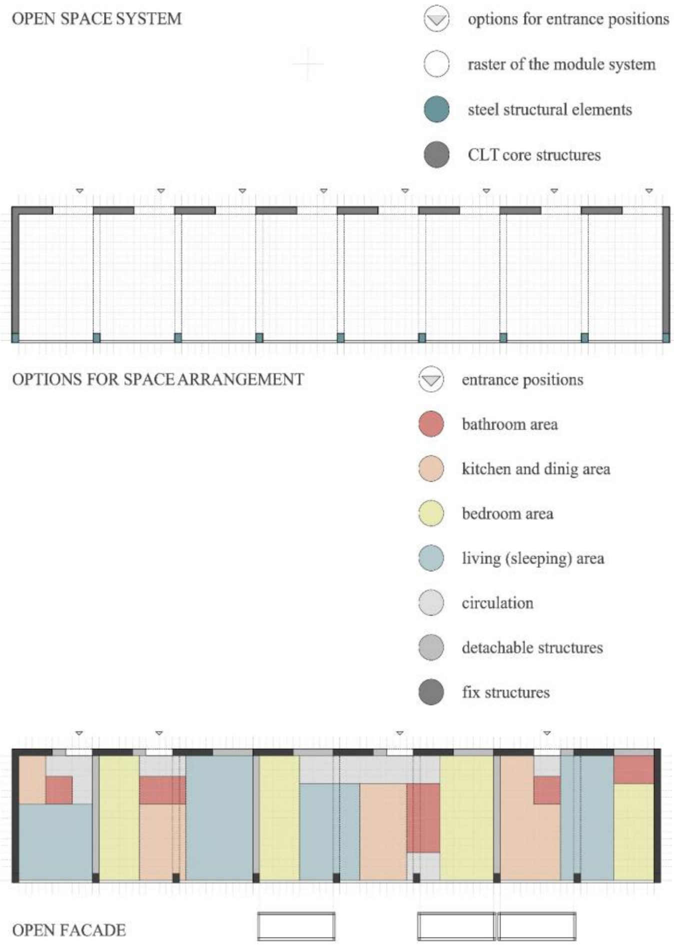


Figure 3. Adaptability of the living space

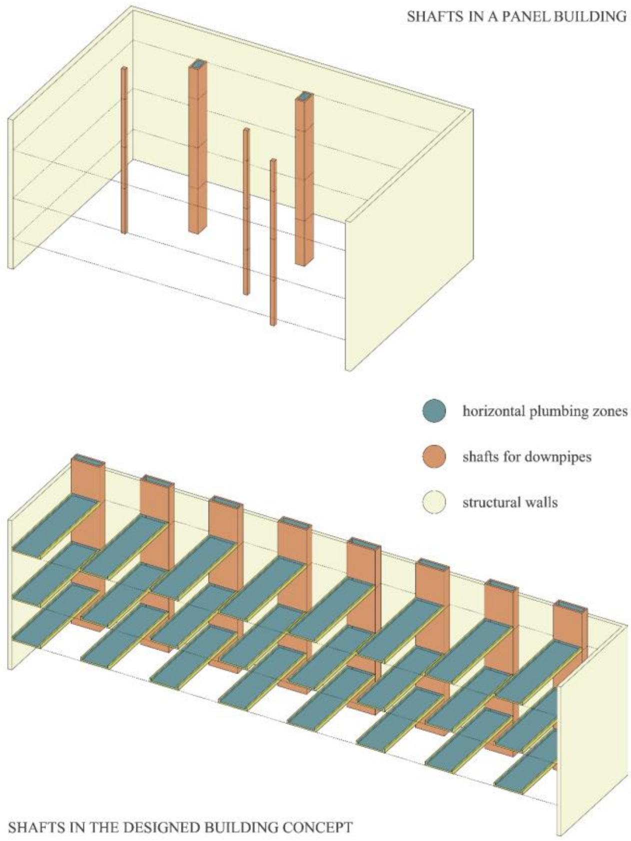


Figure 4. Possible placement of the building mechanical systems

Aside from the structural constraints, the modifiability of "panel" residential buildings is further impaired by limited access to the building's mechanical systems. The prefabricated box-type wet rooms are connected to vertical shafts running through the building as shown in Figure 4. These shafts allow for access only from inside of the living spaces, and thereby severely restrict the possible floorplan variations. A single access point for the plumbing would still allow for radial connectivity; however, the fixed inner walls make that unachievable. Additionally, the slabs and beams further restrict the building's mechanical systems, and, in turn, the placement of wet zones. Since the flooring is directly attached to the reinforced concrete slabs, there is a good amount of space in which plumbing cannot be placed.

The modification of a building's mechanical system may be necessary for two reasons. (1) The needs of users change over time and (2) mechanical systems may become obsolete due to technological change. Both of these occur more rapidly as more energy efficient and environmentally conscious solutions are considered, which develop at an accelerated pace. Updating the mechanical systems should be feasible, in order to maintain the functionality of the living spaces. For example, this could be accomplished through the building design, by placing the shafts for downpipes outside of the living spaces and supplementing them with horizontal plumbing zones. These zones under the flooring create a mechanical compartment and connect into the shafts. The wet areas then connect into these plumbing zones and could more flexibly be placed on the floorplan, since the traditional access points are substituted here with access zones. Another key part of the solution is making it possible to disconnect from the plumbing zone. This requires accessibility to the plumbing zones, which is provided through raised flooring.

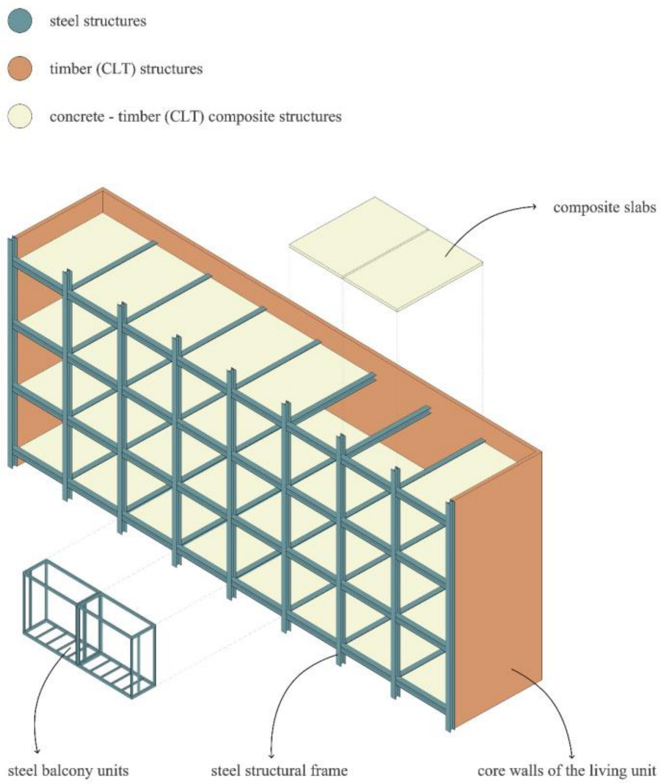


Figure 5. The proposed composite building system

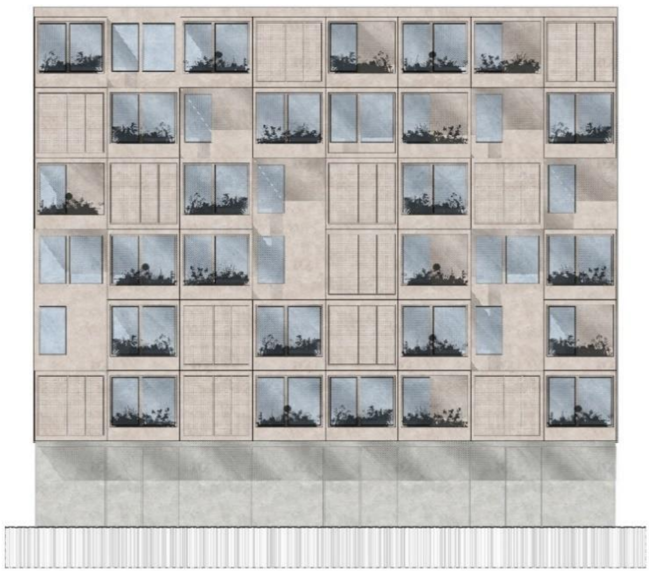


Figure 6. Facade of the apartment building with a possible combination of the interchangeable balcony units

The proposed building concept uses prefabrication of the structural elements. The deficiencies of prefabrication were minimized through the selection of proper materials, which allow for demountable connections of the mobile space delimiter elements. In light of the above, the building incorporates three main load bearing structural elements, see Figure 5.

In examining the life-cycle assessment of the timber construction material, it was found that ecologically and energetically engineered wood is one of the most sustainable building products [18]. Therefore, for the structural walls, the cross-laminated timber (CLT) material was adopted [19]. Cross laminated timber, an engineered mass timber product, in the form of lightweight and dimensionally stable panels, provides for two-dimensional structural behavior. CLT allows for CNC machining, ensuring high quality and fast on-site construction.

In order to maintain natural light and flexibility, the façade of the living zone was designed to be as open as possible. This was accomplished through the use of a steel structural system and bolted connections, which ensures the slimmest structure and incorporates custom configurable steel balcony units, respectively. The variability of the façades can be increased by including various sized windows and shielding elements (see Figure 6).

The horizontal load bearing structural elements use a combination of the materials mentioned above. The main steel columns and CLT walls support the steel beams, which support the CLT-concrete composite floor slabs. timber-concrete composite floor system [20] ensures the most structurally efficient use of the timber and concrete materials. In such a floor slab, a layer of concrete is bonded during casting to the top of a CLT layer. Structurally, the concrete layer is loaded in compression while the CLT layer is in tension. The thickness of the concrete layer is significantly reduced compared to a traditional reinforced concrete floor solution. Alternatively, due to the particular geometry of the building floor plan, which results in a mostly one-way loaded slab (Figure 4), a solid unidirectional timber layer [21] can also be used in lieu of the CLT. The composite system provides higher strength and stiffness when compared to timber-only floors. In addition, the CLT layer serves as the formwork for the concrete layer, which reduces the cost of the floors when compared to reinforced concrete slabs.

5. CONCLUSION

An adaptable, modular building concept was proposed, creating a prefabricated residential building without fixed structures in its living zone. The freely adaptable interior space can easily meet the rapidly changing social needs for buildings and results in an elongated functional lifespan. In contrast to the existing mass-produced Hungarian residential buildings, the concept presented in this paper allows for reorganizing the apartment layouts with no impact on the loadbearing system of the building, as the connections between the interior partitioning elements and the structures are detachable, a key element to achieve structural adaptability. Thus, the structural lifespan of the building is also extended. As a next step in the research, these structural details will be thoroughly designed in order to meet the various structural and acoustic requirements. The long lifespan of the building ensures that its energy needs are minimal. With the use of an optimal combination of construction materials, such as cross laminated timber, steel, and composite CLT-concrete, a structural system consisting of mass-manufactured members can be created, that could be assembled on site without a need for special qualifications. This leads to further energy efficiency and waste reduction. As the secondary structures of the building are demountable, these elements can easily be changed in case of renovations or future material modernization.

Today, the cost of prefabrication is greater than the traditional building methods, which results in a greater construction cost. However, as the lifespan of the designed building is extended, the capital cost can still be competitive.

Harmonizing the structural and functional lifespans of the building results in an improved, economically and environmentally sustainable design, that is capable of addressing some of the challenges of continuing global urbanization.

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