Modular timber structures

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Modular timber structures

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Abstract. Related to sustainability movement and minimizing the carbon footprint, timber structures are becoming more attractive. Wood, as main structural material, offers many benefits relate mostly to economic and ecological aspects, compared to other materials as steel or concrete. On the other hand, physical characteristics of wood complicate the usage of a timber for high-rise or large-span structures. It brings a new challenge for architects and engineers to deliver feasible solution for usability of timber, despite its features. One of the possible solutions could be implementation of CLT (Cross-Laminate Timber) panels in structural systems developed earlier for buildings made of prefabricated concrete slabs. SOM in cooperation with Oregon State University are currently testing composite slabs made of CLT and thin concrete layer reinforcing the wood and protecting it from fire. Although the system solution looks promising, and could bring the result, slabs limit using of the space in layout. On the other hand, frame structures would be much more efficient. This article comes up with an idea of modular frame structure, which could help to solve the problem. The scheme is based on “gridshell” type systems, where rods form a more efficient shell for dealing with stress forces.

1. Introduction

Currently, glue laminated timber is commonly used in standard buildings. For high rise structures (HRS) and long span structures (LSS) wood, as a main structural material, is used only sporadically. These structures are mostly experimental buildings and the project that usually requires specialized software which is developed exactly for designed structure. On case studies related to finished and experimental buildings, characterized by load bearing timber structure, is based on a development of universal structural prototype, which can be used for timber high rise buildings. The system is supposed to be universal and should be able to meet various architectonic and space requirements.

2. Case studies

Excellent example of load bearing frame timber structure can be seen in Tamedia Office Building in Zurich, Switzerland - ‘Figure 1’.

Figure 1. Tamedia Office Building.

Structural principle of Tamedia is actually pretty simple. It is a six-storey high frame structure made of a glue-laminated timber - 'Figure 2'. Wooden beams and pillar in the whole building are not covered and are protected from the weather by a transparent façade, which makes the whole interior structure visible from outside. An important element is using of joints – architect Shigeru Ban designed them according to traditional Japanese carpentry techniques called "Miya-daiku" and "Sukiya-dayiku". These joints are made only of wood - 'Figure 3', which eliminates need of other material for the structure.

Figure 2. Tamedia – structure.

Figure 3. Tamedia – joint.

For a better distribution of stress in frame structure it is possible to use a system called gridshell. This structure is characterized by (usually double) curved plane made of rod type elements. Grid is usually orthogonal, but also irregular schemes exist. We can illustrate the principle on Trondheim gridshell - 'Figure 4', an experimental structure builds by students of Norwegian University of Science and Technology.

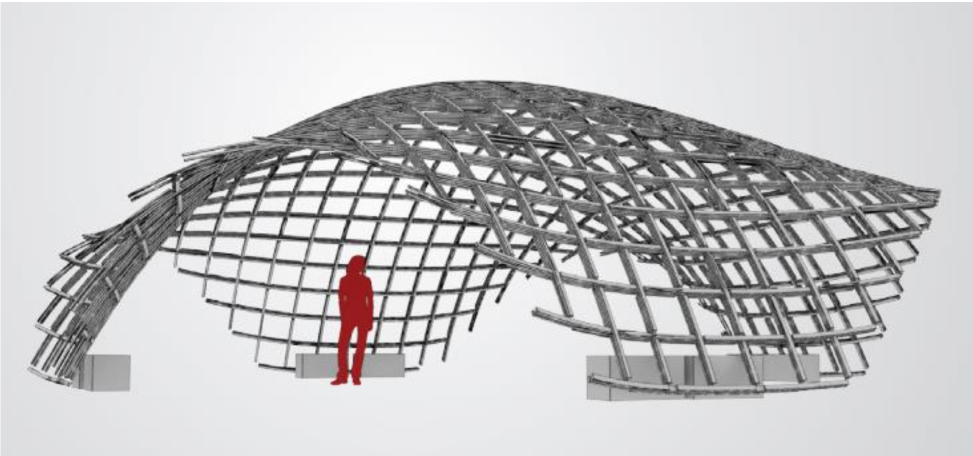

Figure 4. Trondheim gridshell – model.

The structure is a result of large analysis of existing gridshells and following development of the optimal form (curve) of the shell. There were used parametrical software for the form finding phase and special computing add-on software for optimization of the parameters. The final structure is based on orthogonal planar grid. The final shell was reached by deforming the structure by rising the centre of the grid and fixing its foundations. The structure is then actually pre-stressed therefore, more effective in diverting the load.

Orthogonal gridshell systems are suitable for regular forms of shell. For free (organic) forms, like Pompidou Metz - ‘Figure 5’, it is better to use more sophisticated systems. The entire building is wrapped in a fabric-clad hexagonal layered gridshell. The architect, Shigeru Ban, found inspiration in woven canework of traditional Chinese hat. Each of three layers of laminated timber goes in different direction, forming a hexagonal net. Timber blocks are added between the layers, which increasing the depth of structure and thus the structural performance of the system [1] - ‘Figure 6’. The final approximately 90 metres wide 80 metres high structure is then very rigid and stable. The shell was divided into elements, which were prefabricated using CNC machines and assembled on site.

Figure 5. Centre Pompidou Metz.

Figure 6. Centre Pompidou Metz – structure.

Potential of usage of frame structures seem to be limited due to physical-mechanical characteristic of wood. Pillars and beams have to be very massive to bear the loads from upper storey and possible bending moments caused by wind. As an attractive solution seem to be implementation

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of slabs in the structure. CLT (Cross-Laminate Timber) panels can create a “box” system, which is much more stable. One of these systems was firstly presented and patented in Czech Republic in 1964 by prof. Ing. Václav Rojík, DrSc. The structure was firstly developed for reinforced concrete buildings, but has never been used. Research based on the original system using CLT panels is currently underway [2]. According to parametrical models, the high of twenty or more storeys can be reached with using only 150 mm thick panels.

3. Possibilities for high-rise buildings

The question is, if we can use the knowledge from existing structures to develop a frame system for high rise buildings. Static and material disadvantage of wooden rod elements were already mentioned in this article. Nevertheless, the solution mentioned above is relevant only for the specific case and cannot be applied generally. The system is usually developed for specific use regard to architectonic design. For general use of the results of the study it is necessary to develop a universal timber structure system. This system should provide sufficient freedom in design and possibilities in usage of space according to functions (i.e. housing, administration, etc.).

The key attribute for designing a universal system is modularity. Module is an integral part of structure, represented by a single construction component, a segment of structure or the whole part of the building, i.e. a functional unit, story, etc. By repeating the basic module we should reach many different structures. Module should be also simple for prefabrication, should be easy to connect to another module, transport, etc. Problem obviously comes with using the same universal module in different part of the structures or building, where different requirements for use of space or typically for HRS and LSS in different types of stress are identified. Because the frame structure creates a free space (according to Le Corbusier´s “Plan Libre") it is ease to design different layout in to the same modular structure. Complications come with variable requirements related to structural stability.

Generally, three principles can be used as a basic solution approach. Modules can be designed for the maximum of stress forces found in the structure, which leads to a waste of material in less loaded modules. Unnecessary material in upper storeys causes additional load for lower parts of the structure, so these parts must be designed for higher load than would be necessary.

In a nutshell, it is possible to design special modules for different parts of the building. Nevertheless, as there are always different specifics and requirements, it will inevitably lead to lose of universality in the system due to specification of its parts. Another possibility is the application of reinforcing parts, like monolithic concrete core or steel parts, which also lowering the universality of the system - ‘Figure 7’.

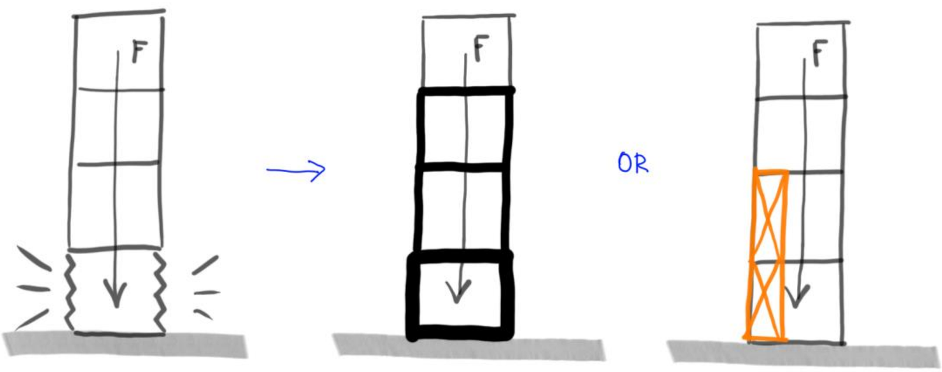

Figure 7. Stability.

This article presents another possible way of designing the structure. If there are variable requirements, the module needs to be also variable. To maintain the universality of the system, the module must be adaptable according to clear principle. This principle should be able to react to as many different requirements, as possible. The promising approach could be the fractality principle.

4. Fractals

Mathematical definition says that fractal is a subset of a Euclidean space for which the Hausdorff dimension strictly exceeds the topological dimension. Better definition is "A fractal is a shape made of parts similar to the whole in some way" [3]. The principle could be easily explained by the following picture of "Sieprinski Carpet" - 'Figure 8'.

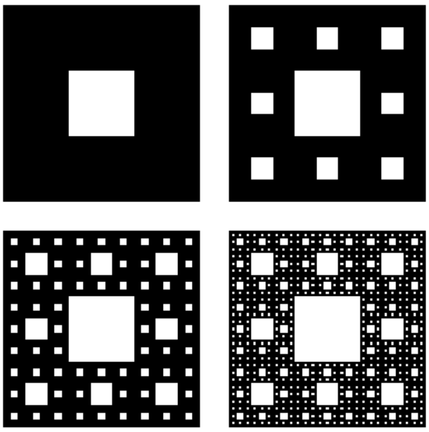

Figure 8. Sieprinski Carpet.

5. Fractal modular system

The idea of the system is the replacing the standard module by a predetermined number of sub-modules according to structural and space requirements. The easiest way of application is to define a module by the standard height of one storey - 'Figure 9'.

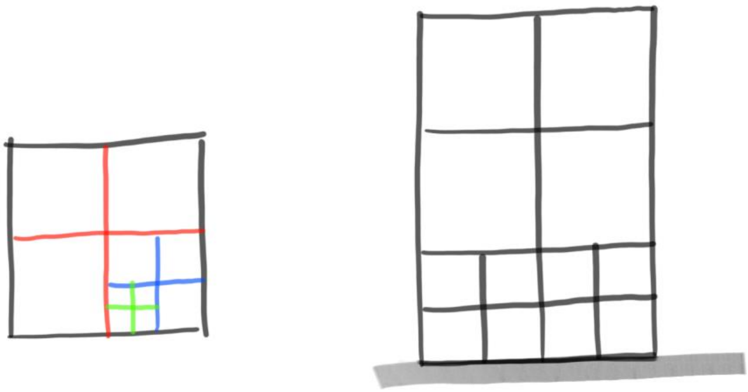

Figure 9. Basic principle.

6. General theory of structures for high rise structures

The idea works well for vertical load, but rectangular frame is not very effective in resisting to horizontal stress. Especially in high-rise timber structures, which are very light and also height (for standard housing unit can be the weight of timber load bearing structure set to about fifteen tons, compared to concrete, which is generally between 30 to 60 tons per unit), bending moments and twisting caused by wind are very dangerous. The module, on its own, should be stable to improve the aspects of the whole structure. The most stable geometric shape is triangle, so the final system should include it.

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7. Geometry

The geometry of the system described in this article is based on a square, which diagonal has a dimension of one story – in this example its three meters. Modules connected together are creating one grid, so the structure is based on load bearing facade, as same as in professor Rojík´s system. Floor slabs or grid-slabs can be attached to joints of modules that repeat every half-storey height. Each module can be divided into sub-modules, according to structural requirements. Standard module height is suitable for housing (according to Czech legislation), one and half module is perfect for administration. Other possibilities can be found on the following picture - 'Figure 10'.

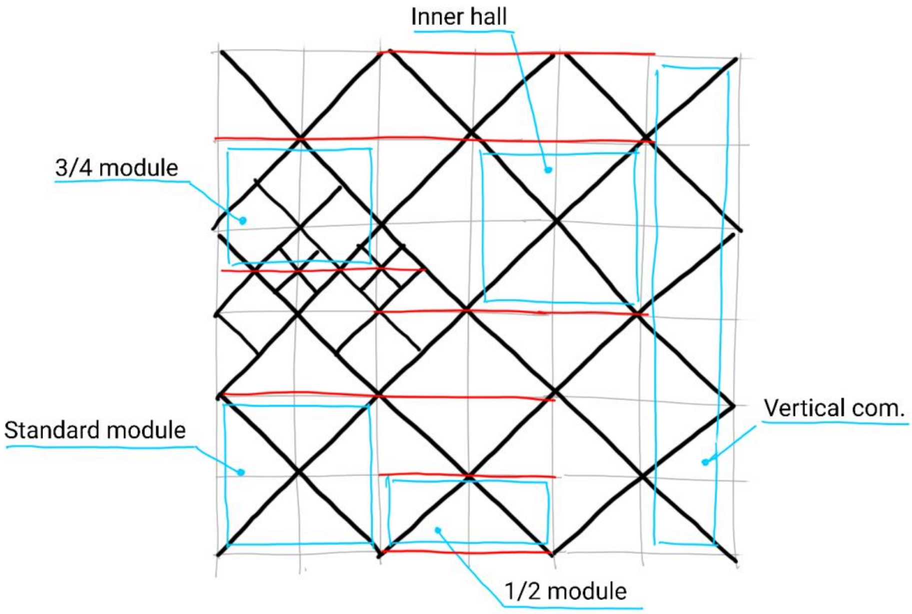

Figure 10. Geometry.

8. Application

In design phase of the building, the system is used as free shape load bearing façade. In the layout, the shape of the structure is free. It may be orthogonal, but also free curved shapes are possible. It is preferred to make multiple layers forming inner atriums or caverns. The final shape of layout could significantly improve the stability of the whole building. It is possible to create tilted facades, forward or receding stories. There are only several conditions which needs to be always followed as to keep the module planar and to keep it in the consistent dimensions (twisting and scaling needs to be avoided). The free shape of the structure makes the load bearing facade to distribute loads similarly to gridshell structures.

The dimensions of section of laminated timber beams are assumed to be 300/300 mm. Clearly the most important part is the joints. It is possible to use steel segments, but the general aim of this research is to maximize the use of timber. Similarly, as in structure of Tamedia, it is possible to use traditional carpentry techniques to connect the modules. It is possible to connect modules together in main connections by using the traditional joints. Also, additional connections in sub–modules can be created by the same principle. All timber part should by prefabricated on CNC, but also it would be possible to make a joint in-situ.

Floor slabs are also formed by the same grid modules, only horizontal orientation is considered. If needed, modules can be reinforced by dividing into submodules or adding vertical modules. As the result, the finale structure should be very rigid. As the protection from the weather condition a double transparent façade anchored to modular structure can be used.

On the next pictures there is presented a twenty-storey high building which is designed by using the modular system. On the left side -'Figure 11.'- there is the load bearing structure, right side - 'Figure 12.' – there is the same building viewed in x-ref mode.

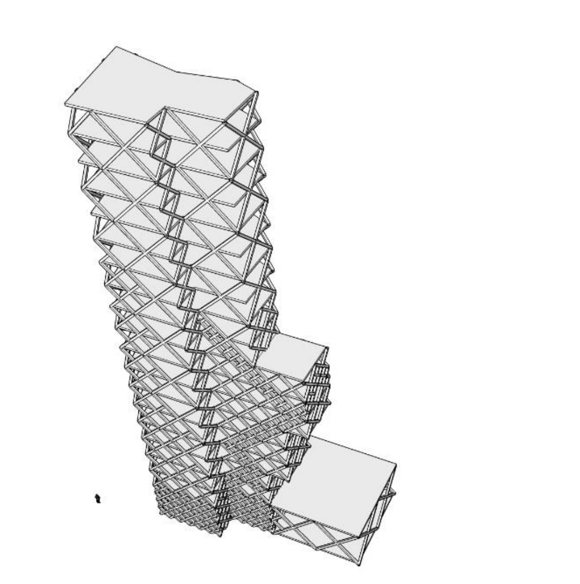

Figure 11. Application.

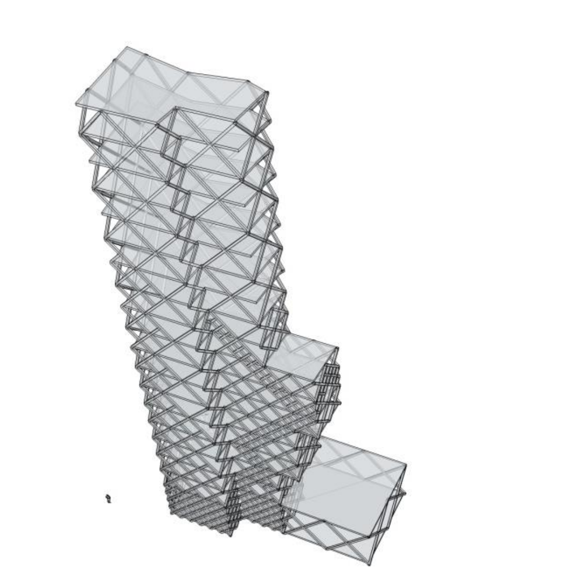

Figure 12. Application – x-ref

9. Conclusion

The aim of the research is to find a modular timber structure for high-rise buildings. The modularity of the structure makes the system very universal. By using the same principle for different types of buildings and repeating the same principle, a great amount of energy can be saved in developing the software and can be used for deeper development of the structure.

Although, there are still many parts of the system that need to be developed. This article shows the general idea and the possible approach. Next possibility could be layering of the structure, as demonstrated on Pompidou Metz roof. Combination of structural layers could simplify the joints of each module, could bring material savings and improve mechanical performance of the system. Effect of replacing the one joint in specific spot between modules by multiple joints on different spots of every layer is now in testing phase.

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