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# Modular Timber Gridshells

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Needs of considering environmental impacts and growing emphasise on using renewable resources is discussed also in the field of architecture and construction. Timber, as a key element, provides certain benefits with less negative environmental impact than non-renewable resources, represented by commonly used materials (e.g. concrete). Nevertheless, using the timber as a core element for constructing of multi-storey or large hall buildings can be more difficult due to limits of the wood. New task for architects and engineers therefore arises and the target is to come up with a feasible solution for using the timber as a core material, despite its features. One of the key requirements for wide use of load bearing timber structure systems is "modularity". Many different forms of structures can be achieved by repeating the basic module to fulfil architect's intentions. This article focuses on a large-span structure, based on gridshell type systems. Such modules could be simply prefabricated and connected to another module. Modules can be pretty small, which contributes to easy and cost-effective transportation. Nevertheless, technical requirement and limitation of such modules needs to be taken into consideration. Problems come up with using the same universal element in parts of structure with different character of load and stress. Also, universal element should fulfil various space and form requirements set by architect. Suggested construction system is based on "fractality". The goal of the system is to fulfil requirement of final structure and space requirements by replacing the standard module by a predetermined number of sub-modules. Structure is then denser in exposed areas and sparser in others. Design module is than expected to be tested and put into practice for wide usage in construction projects where wood is desired as the core material.

**Keywords:** fractality, gridshell, modular structure, timber.

## Introduction

Gridshell structures can be considered as a new trend in architecture. Especially structures made of timber are becoming more popular among architects. Experimental structures are being designed and constructed not only on premises of universities, but also architectonic ateliers are running testing projects and exploring opportunity of using timber structures. A good example of a timber gridshell structure can be found also in such a reputable studio as for example Shigeru Ban architects (Centre Pompidou Metz or Nine Bridges Country Club). Nevertheless, most of these structures are built on the unique structural principles which are specific for the project. It mostly needs a software solution tailored to the requested structure.

The goal of the article is to define the requirements of universal modular element for gridshell-type structures and identify applicable solutions for designing it.

The article is aimed to possibilities of modularity in schemes of gridshell structures. By using standardized system instead of customized solutions there will be achieved economies of scale due to simplification of designing process, structural stability calculation and cost effectiveness in production. These aspects would further lead to overall cost reduction and therefore cheaper construction which can be widely used.

The first part of the article is focused on analysing the existing timber gridshell structures based on different systems which are in the phase of a study, a project stage or realizations stage. It is pos-

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sible to identify the key features of system by analysing the constructing principles, that is essential for developing the universal modular structural system. The new system should be able to flexibly respond to specific demand for usage of space and other requirements of constructors. This part of the article also defines theoretical backgrounds based on the analysis of realized constructions and consequent synthesis of individual construction approaches. The analytical part is divided into three subsections summarizing the main directions of structural design.

In the second part of the paper, the principles, defined in the first part, are extended by other generalized requirements for the resulting principle. The universal construction system is examined by the method called research by design.

Several studies examine the research of wood-based gridshell constructions (for example form analysis created simultaneously with Trondheim gridshell development by students at University of Science and Technology in Norway or the work of Jun. Prof. Dr. Christopher Robeller at Technische Universität Kaiserslautern). The current research in this topic goes from "form" to "structural element". It means, that final structure is developed prior its structural elements. In this article, I will start with structural principle represented by the "structural element" to possibilities of final forms. Therefore, the structural elements proposed in this article can be used for various forms of structures instead of the original one.

## Analysis

In general, if gridshell structure is designed properly, it excels in distribution of stress. Such structure usually features by double-curved surface which is based on the rods. Grid is usually rectangular. Nevertheless, there are identified more complicated irregular systems too. The core principle can be illustrated by Trondheim gridshell (Fig. 1), an experimental structure, which was built on University of Science and Technology in Norway.

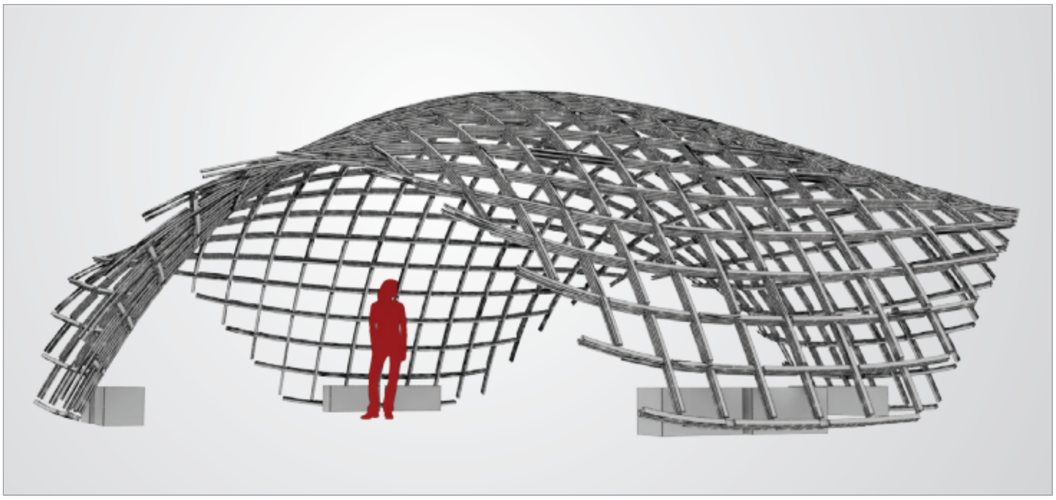


Fig. 1
3D model of the Trondheim pavilion

This structure was widely analysed in previously published article called "Modular Timber structures" published in journal IOP Conference Series: Materials Science and Engineering 2020.

The structure is formed by rectangular grid, where the layers are going in two orthogonal directions. First part of the designing process was focused on defining the proper curve (shape) of the shell. The whole project was designed in parametric software, where the final form was reached by changing parameters (defining algorithms). Also, special attention was dedicated to joints of layers and rods itself in regard of used type of wood. The final structure was archived by raising the centre of planar grid and fixing its base. The final shell is then very effective in diverting load because it´s pre-stressed character (Kuda, Petříčková 2020).

Fig. 2
Centre Pompidou Metz

Fig. 3
Centre Pompidou Metz – element

The grid in the previous example is strictly orthogonal and then applicable only for smaller and regular shapes of shells. For larger and more organic structures more rigid scheme is needed. By adding a layer which is going in third direction a hexagonal grid is achieved. This type of gridshell was used to construct the roof for museum Pompidou Metz (Fig. 2) designed by Shigeru Ban and inspired by canework of Chinese hat. *Each of three layers of laminated timber points in different direction which forms a hexagonal net. There are added timber blocks between the layers, and it increasing the depth of structure and thus the structural performance of the system* (Silver, McLean, Evans 2013) (Fig. 3)

The gridshell, which covers the museum installation, is 80 metres high and 90 metres wide. Although, the performance is very similar to Trondheim gridshell, construction method is different. The structure is made by unique CNC prefabricated elements, as can be seen on Fig. 3. Elements were then joined together on site by metal plates and screws.

Fig. 4
Laser cut dome I

## Laser Cut Domes

Previous examples are based on “continuous” beams which are tangled in different directions to form a plane. This type of construction usually requires steel as a connection material of wooden pieces.

Fig. 5
Laser cut dome III

Another approach is to construct a gridshell from several different prefabricated pieces (Fig. 4, Fig. 5). The construction consists of parts which are designed on the principle of rods and joints with exact dimensions calculated based on requirements for the shape of a final structure. Exact dimensions of the pieces are subject to sophisticated software. The form of the structure is than geometrically very strict and therefore not variable and adaptable. On the one hand, the limitation in variability makes the prefabrication of pieces easier, because all parts of the structure are similar. On the other hand, it is applicable only for basic geometrical forms such as a dome or an arch. Although these systems are considered as very useful, it misses the element of customization and adaptability to imperfections of the structure.

A new joinery system composed of interlocking plane pieces was introduced by Lauren Johnson in paper presented at PUARL conference (Fig. 6). System is based on vertically oriented triangular modules, flexibly connectable to each other without fixed joint. The joint than offers the certain level of flexibility. As a result, it is possible to reach a double curvature in form without alternation of the geometry of modules (pieces). The system was inspired by conventional brick masonry.

Although the idea of flexible gaps between modules is interesting, it brings the questions if larger structures which will be using this principle will offer sufficient structural stability (Jihnson, 2020).

## Segmental plate shells

Different system for creating free-form shells was introduced by Jun. Prof. Dr. Christopher Robeller (Digital Timber Construction, Technische Universität Kaiserslautern). This system uses CLT (cross laminated timber) plates, which are connected by wooden wedged joints. The first prototype, The Timberdome (Fig. 7), was built from completely prefabricated pieces, entirely made of wood. The final structure was very strong while lightweight. One of the key conditions for this type of constructing system is existence of very precise CNC fabrication and parametric software (defining all unique pieces). The same principle was also used in bigger dimensions in Recycleshell (Fig. 8) (DTC 2020).

Segments made of CLT panels have limits in thickness, which means the whole structure is limited by maximum dimensions of panels. This “disadvantage” was mitigated in next project, called HEXBOX Canopy (Fig. 9), introduced by prof. Robeller and his team. The basic segment is replaced by prefabricated plywood box component (DTC, 2020).

Modular segment represented by box instead of plate allows a larger static height of the structure. As a result, shells with much bigger span can be achieved. Investing in a smart geometry of the structure is, in the final stage, cheaper than using the material in less efficient manner. Also it can lead to overall lowering of consumption of unnecessary material and therefore positive environmental impact.

Fig. 6

Interlattice

Fig. 7

Timberdome

Fig. 8

Recycleshell

Fig. 9

HEXBOX Canopy

## Possibilities for modular gridshells

The question is, whether the knowledge from existing structures can be used for developing a modular system exactly for organic form of structures. Insufficiencies of wood in comparison with other materials were already summarized in other papers (Kuda, Petříčková 2020). Unfortunately, the above-described solutions are applicable merely for the specific cases and it is not possible to use them widely. The system solution is usually customized and used only for intended architectonic purpose and for specific design (e.g. Pompidou Metz). So that the system can be used in general it is essential to design a timber structure which will be universal. The target system should enable satisfactory variability in design and purpose of space based on its intended usage.

Based on analysis of existing structures we can describe two basic principles of gridshells, which can be used in modular freeform structures:

**Joint system:** The key feature of the structure is the "joint", which connects all segments. Form of the structure is reached by standardized joints and rods of variable sizes (or segments/modules). Designed form is characterized as set of points (joints) which are then linked. Even though this principle is more favourable for prefabrication and construction, there are severe static limits of wooden joints.

**Plane (segmental) system:** The system was designed in an effort to eliminate complicated joints and to move the "variable of the construction" from joints to the plane modules, to the size of modules. The segments are connected flatly, not pointwise. This makes it theoretically possible to achieve significantly greater spans and variability of the structure.

### Principles of universal modules

To accomplish the design of universal structural system, the key task is to design a repeatable and prefabricable element – module. The problems of performance of universal modular structures which are designed for high-rise buildings were widely described in previous work (Kuda, Petříčková 2020). Unfortunately, the same problems come with long-span gridshell schemes. There are different types of stress in different parts of the structure. To keep structural stability, it must be faced to the different load. As can be seen on Fig. 10 diagram, there are three possible ways, how to approach the issue.

As the first alternative, there is the elementary module, which should be designed according to maximal load arising in the structure. This solution unfortunately leads to waste of material in less loaded parts, which results in an uneconomical structure. The waste of material can be eliminated by designing different elements – modules according to its stress requirements. Nevertheless, it will inevitably lead to lose of universality in the system, as there are always different specifics and requirement for its particular parts. The last approach is to reinforce the critical parts by adding special elements.

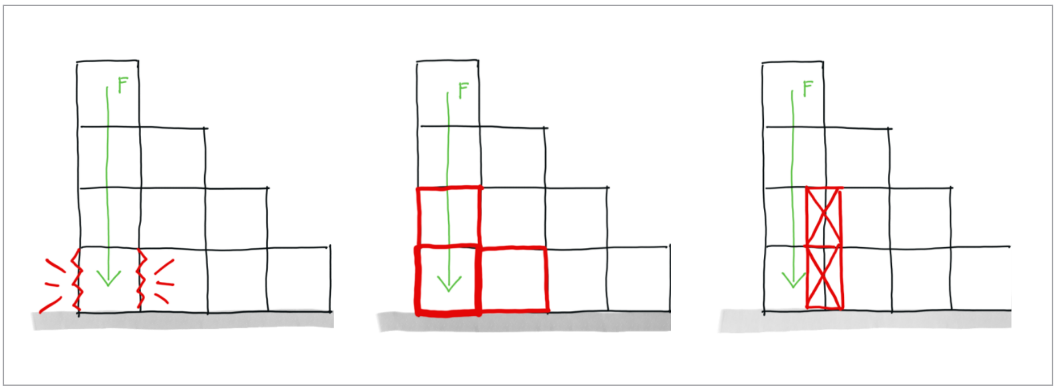



Fig. 10
Structural performance

In the paper Modular Timber Structures, a different approach for facing the structural requirements was proposed, which also keeps the universal principle of the system. The approach is based on "fractality".

### Fractality

*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"* (Feder 2013).

The idea of the system is to replace the standard module by a predetermined numberof sub-modules according to structural requirements (Fig. 11) (Kuda, Petřičková 2020). The structure then works like a three-dimensional net, where the structure in areas with greater amount of stress is denser then in unstressed parts. When the system is modular, it should by also possible to adapt the structure to changes or different requirements. Final building then will be more adaptable to future changes, which will greatly increase its survivability. Furthermore, the repair of such a building in a modular system will be much easier and cheaper, which is one step forward to cost optimization and environmental sustainability.

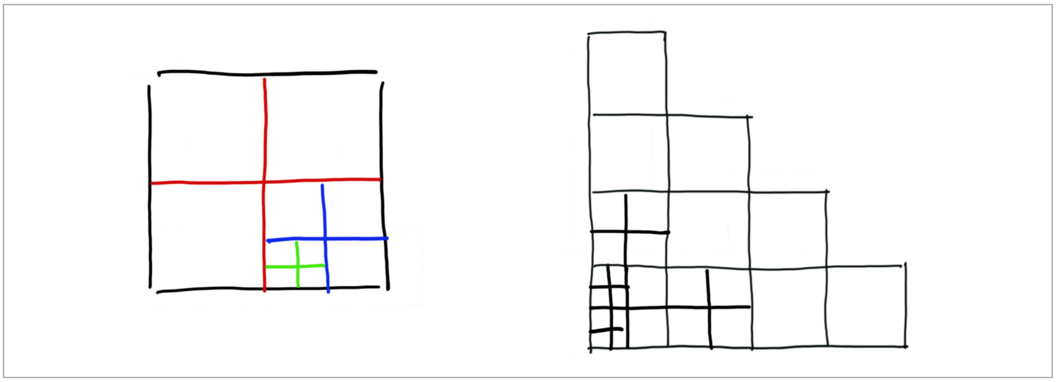


Fig. 11

Basic principle

### Aspects of the module

The core aspects of the module are its structural stability and possibilities of connection to other modules. The previous scheme is based on orthogonal grid, which leads to rectangular modules. For large structures would be better to use geometrically stable elements – triangles. Triangle leads to "three-directional" grid, similarly to Pompidou Metz roof, but eliminates hexagonal parts. Nevertheless, this scheme creates complicated joint – one point, where at least six rods are connected (Fig. 12). Critical part of the module then would be the joint.

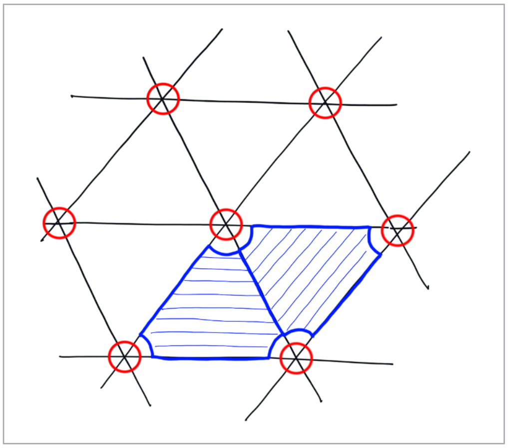


Fig. 12

Geometry – red joints and blue plane segments

### Geometry

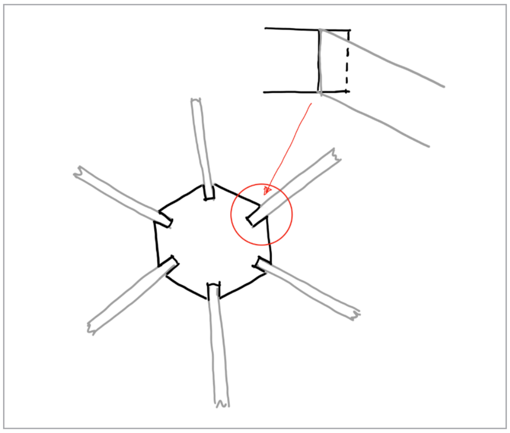
There are two structural principles proposed in this article. The main geometry of both systems (Fig. 12) is the same and is based on triangle. One system is then based on joints (red) and the second on plane segments (blue).

## Application

In design phase of the building, the system is used as free shape load bearing shell. The first system is the “joint” type. Joints are hexagonal plates made of CLT panel with grooves (Fig. 13). Rods are made of timber planks (or glue laminated timber beams). Three joints together with three rods are forming a basic module. Customization of module dimensions is then reached by changing the length of planks and the angle of the cut on its ends. The modules are able to be reinforced by fractally dividing it into submodules. The main disadvantage of the system is the limitation in static performance and thickness of CLT panels. Also, the main joint could be easily overloaded if a bad form and bad geometry is used. Dividing the system into submodules would not be a solution because it does not diverting any stress from the joint. (It only reinforces the module itself.)

Fig. 13

Joint type system scheme



The second system is based on rigid triangular modules. The module is a combination of plywood box system used for HexBox Canopy, laser cut domes and segmental plate structures. The key feature is the displacement of forces from a statically exposed joint (schematically represented by one point) to a contact of surfaces of individual segments (Fig. 14). The connection is achieved by hard wood joints and the surfaces are also glued during the construction. The final structure is then very rigid, each module can be divided into submodules, which reinforce the segment and also help the connection by supporting it.

Examples of application of both systems (Fig. 15)

Fig. 14

Plane (segmental) type system scheme

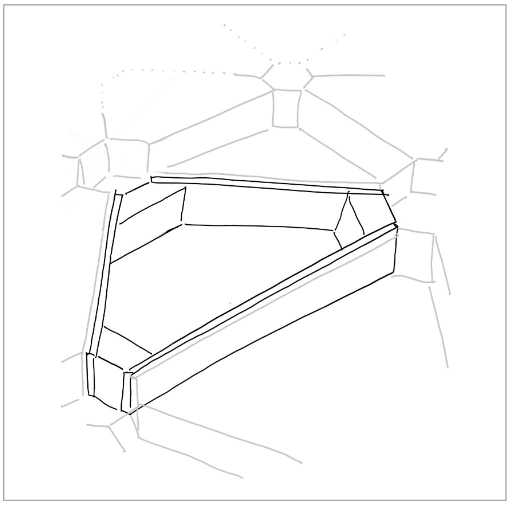
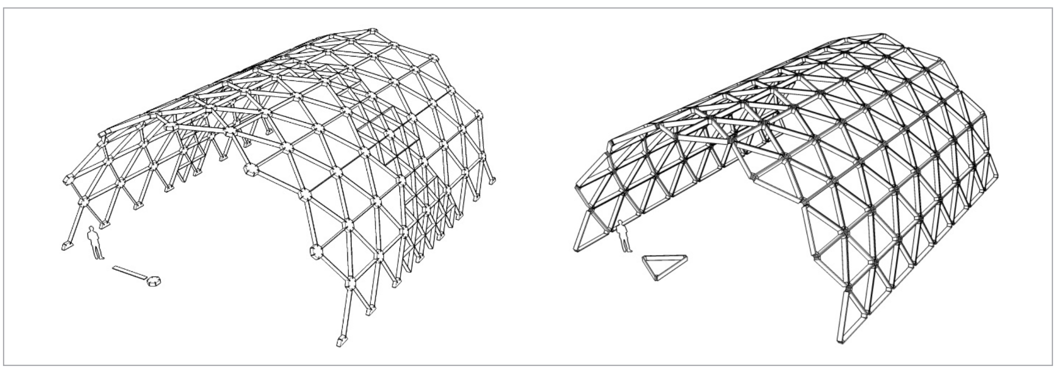


Fig. 15

Examples



## Conclusion

The default network used for a modular gridshell should be based on a triangle. This type of a net provides sufficient stability and possibility of form design. Principle of the structure suggested in this paper is based on segmental shells, whereas connection and prefabricating of laser cut pieces should come from laser cut domes. The principles for setting the shape and distribution of load in the structure are based on principles of Trondheim gridshell and Centre Pompidou Metz.

The proposed modular element is based on the triangle principle. Nevertheless, the triangular network brings complications in the form of complex joints. The article presents two possible modular systems – joint type scheme and segmental scheme. The joint type scheme is suitable for smaller-scale constructions (e.g. pavilions) due to its structurally weak joints.

The second, segmental, system is now in testing phase and supposed to be used for a parametrically defined roof of riding-school in Czech Republic designed by the author´s architectonic office. The span is planned to be about sixty meters. In case of successful usage of the wooden modular gridshell structure in the testing project the system could be implemented and widely used in case of several construction projects where wood is desired as the core material.

This paper summarizes the main idea and outlines the feasible solution to modular gridshell structure development. For the first system a possibility of layering is demonstrated, as it is shown e.g. on the roof of Centre Pompidou Metz. It can result in the savings of material and overall better performance and mechanical properties of the system.

## References

Adriaenssens, S., Block, P., Veenendaal, D., & Williams, C. J. K. (2014). Shell Structures for Architecture. Routledge. https://doi.org/10.4324/9781315849270

Allen, E., & Iano, J. (2011). The Architect's Studio Companion: Rules of Thumb for Preliminary Design (5th ed.). Wiley.

Chilton, J., & Tang, G. (2016). Timber Gridshells: Architecture, Structure and Craft (1st ed.). Routledge. https://doi.org/10.4324/9781315773872

DTC - Digital Timber construction [online]. [Cit. 4.5.2020]. Acessible from https://www.architektur.uni-kl.de

Dyvik, S. H., & Mork, J. H. (2015, May). Gridshell Manual. https://www.researchgate.net/publication/332808217_Gridshell_manual_-_Master_Thesis

Jens Feder (2013). Fractals Springer Science & Business Media 11; ISBN 978-1-4899-2124-6

Johnson L. InterLattice: Parametric Joinery System [online]. [Cit. 17.5.2020]. Accessible fromhttps://archinect.com/people/project/47856646/interlattice-parametric-joinery-system/47862679

Kuda D., Petříčková M. (2020) Modular timber structures, IOP Conference Series: Materials Science and Engineering; 800 012033 https://doi.org/10.1088/1757-899X/800/1/012033

Macdonald, A. J. (2001). Structure and Architecture (2nd ed.). Architectural Press.

Salvadori, M. (2002). Why Buildings Stand Up: The Strength of Architecture (Illustrated ed.). W. W. Norton & Company.

McLean, W., Silver, P., & Evans, P. (2014). Structural Engineering for Architects: A Handbook. Laurence King Publishing. ISBN 978-178067-055-3

V. (2013). Av 157/158: Herzog & De Meuron 2005-2013 (English and French Edition). Arquitectura Viva.

Weinand, Y. (2016). Advanced Timber Structures. De Gruyter. https://doi.org/10.1515/9783035604900

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