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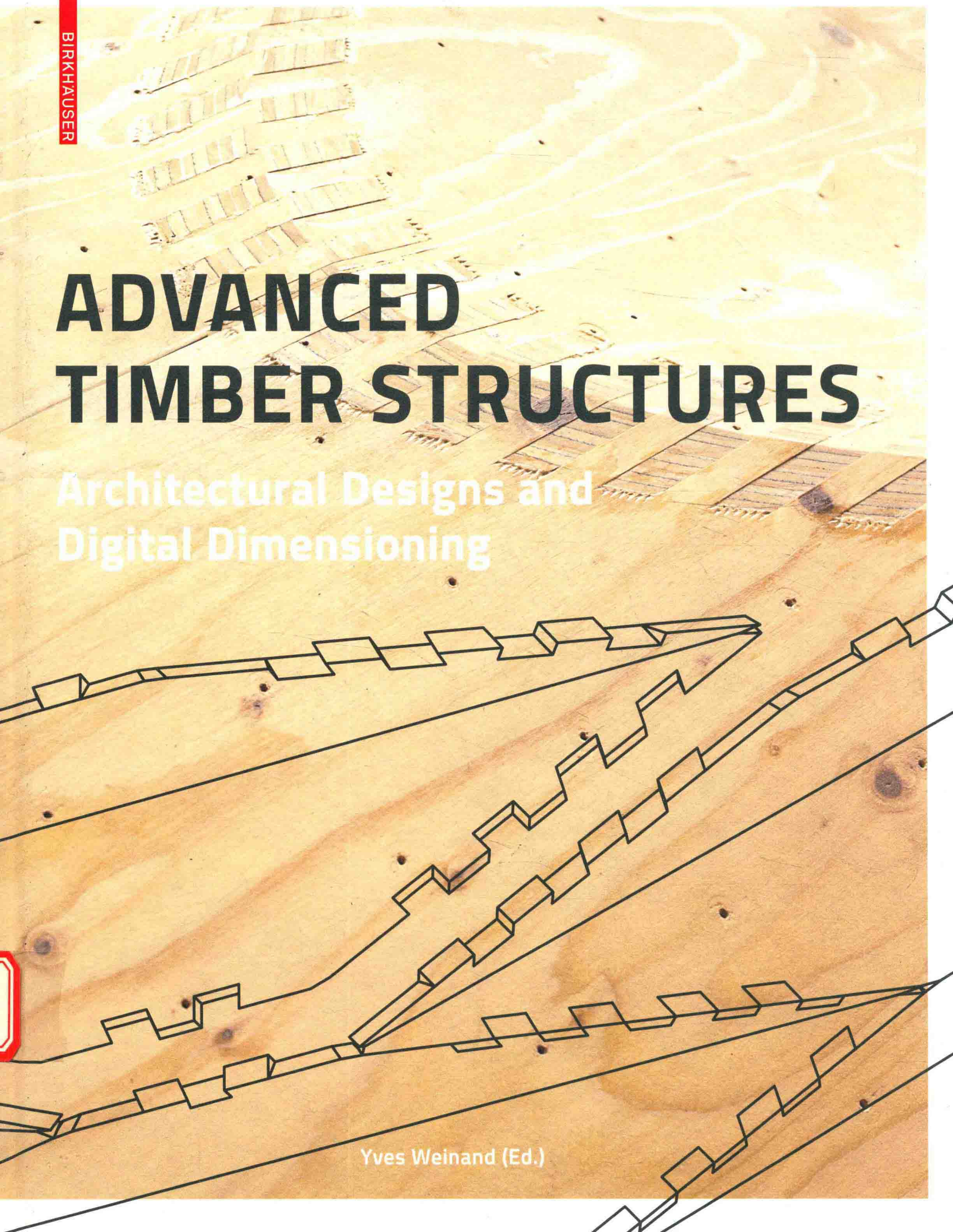
ADVANCED TIMBER STRUCTURES

Architectural Designs and Digital Dimensioning



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Basel

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How can a schedule and a technologically innovative process shift the perspective of the construction industry toward sustainability?

Yves Weinand

Timber construction has a promising future—especially in relation to climate change and our need to find sustainable solutions for the construction industry and to implement the use of appropriate building materials. Timber's comparatively low energy consumption has been a known fact for years. Challenges around sustainability in the construction industry also touch on the question of architectural form. At the Department of Timber Structures, IBOIS, EPFL Lausanne, we posed the question of how a formal and technologically innovative process might be developed from a sustainable perspective. The renewal of construction technologies and technical procedures in timber, taking into account the innate qualities of the material, could lead to the increased use of timber in contemporary construction. This is not about the principle of longevity or permanence, on which modernity is based, "modern" implying that which lasts, or that which remains. Timber is generally regarded as being a traditional building material. This preconceived image is advantageous to socially legitimate research that is about finding complex shapes, or creating free-form structures, when it is done in timber.

Choosing to approach complex geometries from the perspective of the designer, rather than merely in terms of generating forms, can be seen as stepping away from fashionable trends in architecture, especially the free, amorphous forms of so-called "Blob" architecture. Many such free-form buildings completely ignore the problem of sustainability, partly due to their choice of materials and partly due to their energy consumption and the cost of maintenance. In contrast, the savings in overall energy consumption by the use of wood as a building material, in terms of life cycle analysis and demolition, are undeniable. As a natural material, timber requires less energy to produce, to transform, to assemble, and to supply sustainably than other building materials. The public has come to expect this technologically innovative process. Today, public and private clients alike demand novel solutions in terms of both sustainable, high-quality architectural design and construction methods. Architects and planners ought to meet this demand by initiating and guiding innovative processes like the ones addressed here. Furthermore, solutions for so-called "non-standardized" architectural forms that are sustainable and economic should be found.

Sustainability

With the onset of climate change, the concept of sustainability has finally become a central issue for our twenty-first-century society. In this context, the research presented here focuses on the following question: by expanding the applications of wood as a construction material, could its use in the construction of public buildings be boosted?

Regardless of its typology or function, a building always consists of a myriad of small elements. Wood and wood-based materials are made up of the assembly of smaller parts. Solid wood, timber beams, plywood, laminated timber, and laminated veneer timber panels are all produced from the amalgamation of smaller-scale parts. For this reason, the technology of the junction connections should also be considered in the synthesis of these materials in a building. The variety of existing timber materials and the considerable versatility in their application should determine the manufacturing and prefabrication methods.

The aim of the research is to find solutions to a number of questions. We are interested in discovering new construction solutions that can be easily incorporated into hardware stores' offerings, to enable the affordable realization of unconventional architecture. One of the most important ways to reduce construction costs is to use a digital design tool. The development of specific, application-oriented digital tools would thus appear to be imperative. Our tools will help at the interface of architecture/civil engineering, mechanical/geometric design, and form-finding/parametric digital prefabrication, in specific, project-related steps.

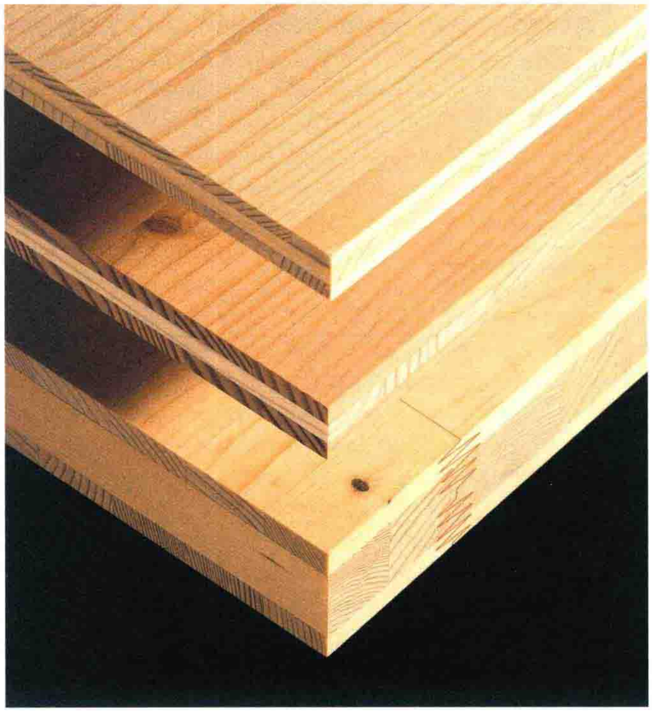


Fig. 1 Three-layer panels

The chair of wooden structures, IBOIS/EPFL

Within the framework of the Department of Timber Structures, IBOIS has initiated various research areas that explore the relationship between engineering and architectural design. IBOIS is part of the Civil Engineering Institute ENAC/EPFL, but it is also affiliated with the Department of Architecture, where an architecture studio is made available to engineering master's students. Thus, collaboration between architects and engineers is encouraged, providing the environment for a wider scientific community within architecture schools Europe-wide. The research results presented here focus on construction and the challenges of realizing complex shapes and free forms. What is the relationship between basic research and applied research? What is the connection between pure research and applied research? Or between curiosity-driven research and problem-oriented research? And finally: how can the scientific research in architecture be reconciled with the artistic dimension of research, in order to bring them into harmony with one another?[1]

IBOIS provides a place to innovate, where the fascinating inductive-experimental approach is combined with the clarity of deductive-scientific methods. This is undertaken with the aim of creating new forms and types of structures—particularly timber structures. In addition to its sustainable qualities, timber also has exceptional mechanical properties, which can be utilized in specific structural forms.

For centuries, timber construction has been governed by the use of linear elements connected to truss systems. However, in contrast to steel and reinforced concrete—the dominant building materials of the nineteenth and twentieth centuries—engineers have done little to develop the use of timber as a building material. Now, thanks to the availability of digital tools, applications of this material can be expanded significantly; new geometries can be created; and innovative construction materials and methods can be developed. In short, we can undertake an innovative exploration of structural engineering with regard to timber. Here, the current ability to use structural planes plays a vital role—for example, large-scale multilayered boards, plywood, or laminated veneer lumber panels.

Innate material qualities of timber

Even today, one can see timber construction as a perpetuation of traditional forms and methodologies. The majority of buildings continue to utilize traditional structures or building methods, such as timber-framing or truss systems. However, due to the availability of new timber-based materials, there is a need to invent new construction methodologies. As opposed to steel or reinforced concrete, building with timber relies to a greater degree on the development of cutting types and junctions, and the understanding of the relationship between them. Thus, for example, when designing a timber building, it is imperative to consider the junctions, which are integral to the structure, and to specify the entire structure, including its joints.

It is essential for engineers who specialize in timber to provide comprehensive details that can be integrated into the overall structure when formulating their structural models. In this way, these engineers take on the role of designers. It becomes clear that timber construction calls for interdisciplinary collaboration between engineers, architects, and contractors right from the beginning of the planning process. In particular, the choice of panel types should play a central role in determining the form and typology of the selected support system.

Characteristic properties	Small Specimen	Constructional Element	Difference to the small specimen
Bending Strength (mean value N/mm²)	68	37	46%
Tensile Strength parallel to fibers (mean value N/mm²)	80	30	63%
Compression Strength parallel to fibers (mean value N/mm²)	40	32	20%

Table 1

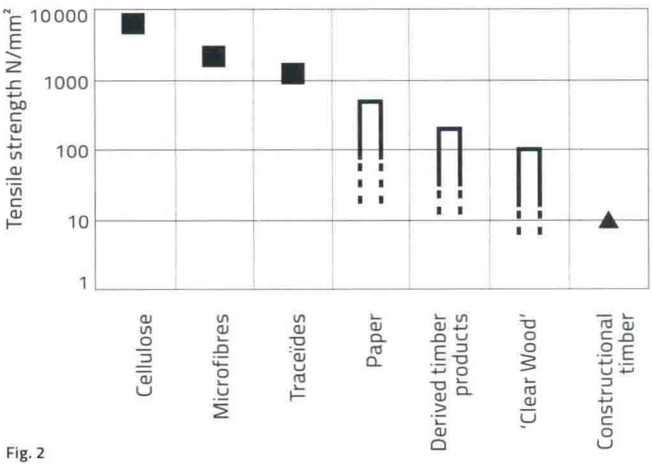


Fig. 2

Table 1 Resistance values for small test elements from spruce

Fig. 2 Development of resistance values for cellulose (f_y = 100 N/mm²) to wood (f_y = 10 N/mm²)

Specifically, the following observations about timber can be listed:

The question of scale

The size of the timber member used determines its strength and hence the range of its applications. Comparatively, a small "clear wood" test block performs far better than a standard-sized beam.

The surprisingly high values of small test blocks (for example, spruce) were categorized by Peter Niemz[2] in table 1. Therefore, great losses in the assessment process can be determined, since in this case considerably lower values were reported.

The anatomy of wood

Figure 3 shows the three principal axes of wood fibers using the example of a cut tree trunk: longitudinal, tangential, and radial alignment of the fibers. In practice, radial and tangential alignments are hardly distinguishable from one another, and an average value is generally taken. The three axes are positioned in a Cartesian axial system. This corresponds to historically applied geometries that define the principles of material strength. A Cartesian axis system describes an isotropic material in an efficient manner, but this is less true for an anisotropic material, such as timber. The longitudinal direction of the fibers, for example, is assumed to be perfectly rectilinear. Though this is partially true, in reality the natural longitudinal orientation of tree growth (i.e., tree fiber) tends to converge conically toward the top of the trunk. More accurate modeling techniques should therefore take into account these specific properties. It would be interesting to develop "tree-specific" mechanical models, such as the scanning of the exact fiber configuration of a particular tree trunk in order to mechanically evaluate a specific application.

The problem of timber anisotropy has already been mentioned, such as in the invention of plywood, where the fibers are confined. If several layers are glued across each other, this results in a homogeneous, or quasi-isotropic, structure.

Systems

A chain breaks as soon as its weakest link fails. In contrast, a system will continue to function even with a broken weakest link. Engineered wood—a dual system of laminated beams, or veneer laminated lumber panels—that consists of several elements glued together can be regarded as a system. These are known as "multilayered systems." The principle can be applied to a specific material as well as to a structural system. A common example is a laminated beam, which consists of several superimposed layers. The resistance value can be adjusted, depending on the number of layers. If the number of layers does not exceed four, then the beam is regarded as a conventional support. If the number of layers exceeds four, then it can be regarded as a system, thereby increasing the resistance of the beam. From the viewpoint of probability theory, the likelihood of failure of a beam decreases with the increase in the number of its layers.

Another pertinent example is a reciprocal system, such as the Zollinger system. If a member of the diamond-shaped configuration of a Zollinger mesh network fails (for example, due to a particularly strong wind load), then the system does not fail as a whole. One also speaks of a "social" support system, where the weakest link is supported by the adjacent members.

These observations lead to the following conclusions:

- It makes sense to produce timber materials where the "system effect" strengthens the total resistance.
- It makes sense to develop structural systems where the interdependency of the elements is maximized.

If these considerations are applied to wood-based materials such as laminated beams, it is foreseeable that, in future applications, these structural systems will also be able to benefit from the system factor.

Traditional carpentry would rarely benefit from a system effect; most of the time, the failure of a roof beam or joist will lead to the collapse of the roof or attic. The same is true for traditional timber connections, where local failure of a connection results in the collapse of the element that is held in place by the connection. The structures presented in the following section consist of a large number of small elements. The importance of developing such support systems, which amplify the mutual dependence of the elements, is reflected in all the structural systems demonstrated below.

A new generation of structures

Can wood perform better than it currently does, or historically has? And could the architectural image of timber buildings be given a more contemporary expression? When one takes a close look at the buildings of Philibert de l'Orme, already envisaged back in the early 1600s, the answers to these questions tend toward the positive.

On the basis of his research, de l'Orme foresaw the use of small-scale wood elements that could be used as an alternative material. He combined this principle with geometric innovations, allowing him to achieve greater spans. Unfortunately, de l'Orme's innovative ideas did not succeed, as they were too labor-intensive: every individual piece and each connection had to be cut individually by hand. These past obstacles to building de l'Orme's structures could be overcome today with industrial fabrication and CNC milling, and the construction could thereby be made affordable. The architectural expression of a networked system can certainly be classified as contemporary.

De l'Orme's findings influenced the French army's military structures. General Armand Rose Emy advocated the use of a large number of small-scale timber elements to cover their arena structures. In this instance, however, the boards were installed horizontally, or rather in a horizontally curved position. Thus the total curvature of the arched structure was achieved by the local bending of each board. This avoided waste; a second advantage was that, as the orientation of the longitudinal fibers of each board coincided with the line of force of the arc, they functioned far better structurally.

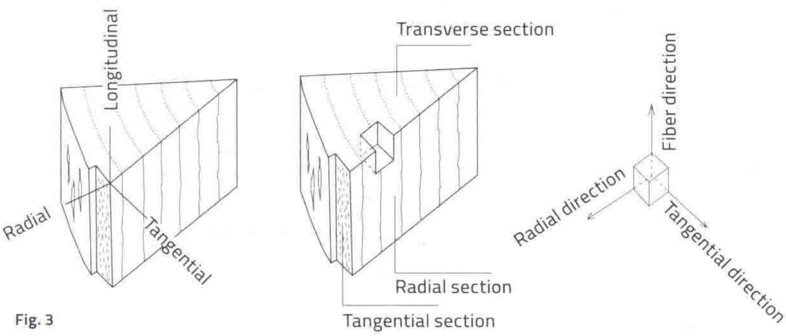


Fig. 3

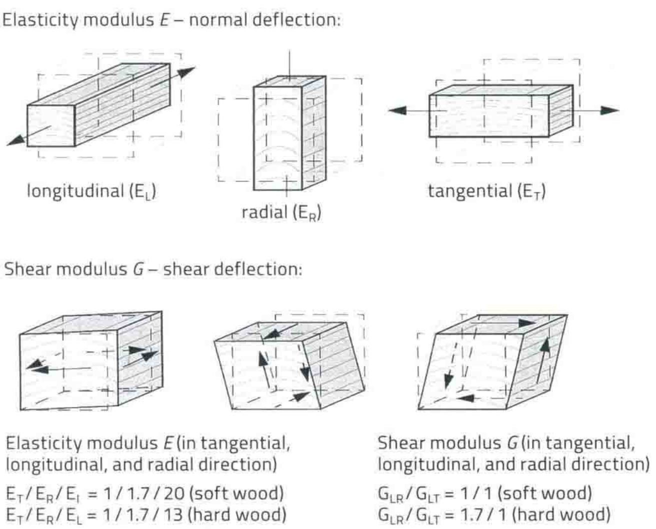


Fig. 4

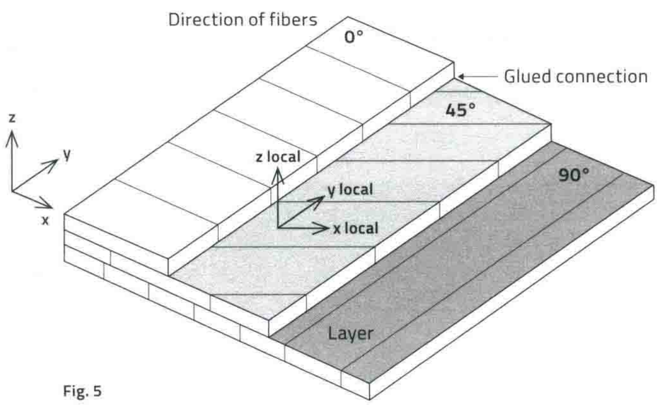


Fig. 5

Fig. 3 The three strands of wood fibers are inserted into a Cartesian axial system.

Fig. 4 Elastic and tangential modules vary greatly.

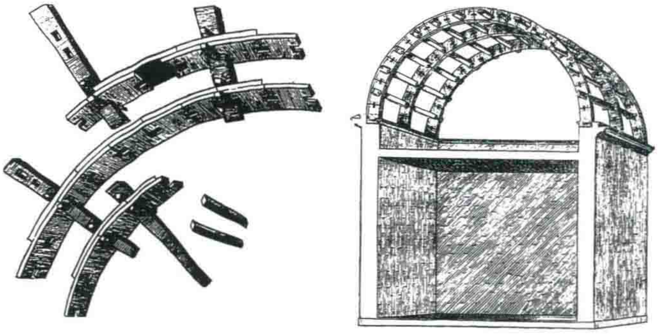
Fig. 5 The principle of cross-laminated timber

The much-celebrated Mannheim Multihalle by Otto Mutschler (1975) is an extraordinary example of a spatial structure composed of networked elements. The double-layered network structure consists of actively bent timber slats with a square cross-section, which follow the thrust line and absorb the normal forces well.

The third and final example of an upgraded structural system is the design for an industrial hall in Botrange, Belgium. The supporting structure consists of simple boards, which are multi-layered and crossed over one another to form a mesh network. The boards pass through the nodal points and are connected only with vertical pins inserted laterally. A spatial structure is thus created out of a complex combination of conjoined small parts. The local rigidity of the nodes can be increased by inserting an additional bolt, thereby increasing the overall rigidity of the system. Timber-frame construction and post-and-beam structures were, and remain, widely used systems in timber. With these composite systems, junctions are added individually on-site. In addition, semi-prefabricated floor elements and wall structures are now available, which can also be incorporated.

As a result, an attempt should be made to create made-to-measure prefabricated systems incorporating connection technologies and precise prefabricated elements. Due to their specific shape or geometry, these custom-made fixtures could only be installed in a specific location and in a unique position within the overall system. Errors that often occur on-site could thereby be avoided.

The manner in which building sites are organized today corresponds, in many ways, to nineteenth-century models. The necessity for a foreman who reads and understands construction plans, and then connects them with the delivered components, needs to be replaced by a stronger and different kind of planning. Access connectivity systems, predetermined assembly sequences, and integral mechanical connection techniques should determine the site-work schedule. For this reason, we are interested in geometric algorithms, subdivision processes, planarization processes, connective sequences, automated milling technologies, tool development, mechanical test trials, and the execution of manual as well as robotic joining processes. IBOIS's areas of interactive research have been summarized in the diagram below. Folding systems, discretized free-form structures, woven and actively bent structures, and mechanically induced structural systems will be presented. Special attention will be paid to the connections.



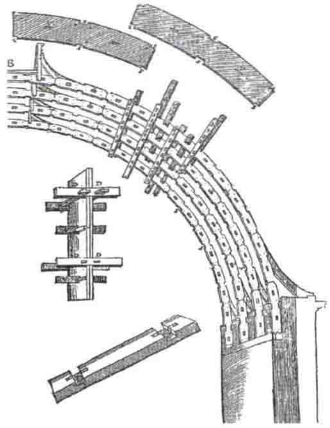


Fig. 6 Philibert de l'Orme: The panels define a part of the curve and are installed vertically. Thus, the edge of each panel describes a section of the arc. A significant proportion of a panel's wood fiber therefore runs into a void, or into the edge of the panel, as it does not follow the primary direction of the curve, as this would require the structural behavior of an arc.

Fig. 6

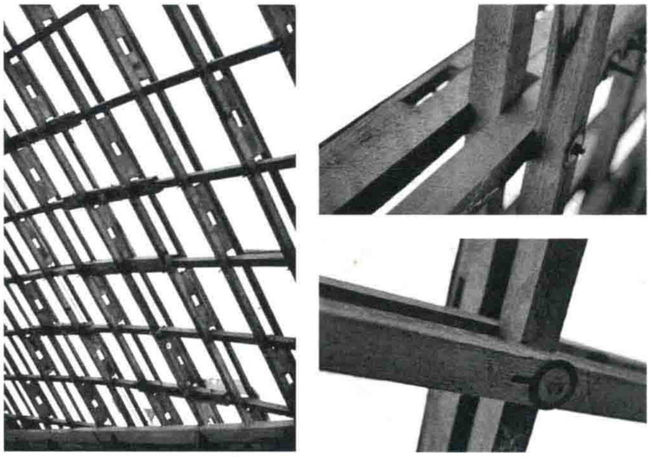


Fig. 7

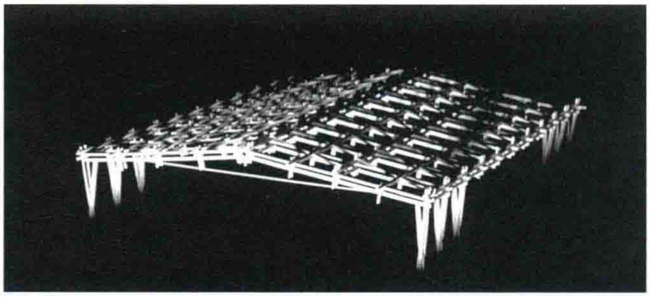


Fig. 8

Fig. 7 Multihalle Mannheim: General view of the shell structure with a span of 60 m. Four rib layers are connected in one node.

Fig. 8 Competition project for an industrial hall in Botrange, Belgium

Notes

1 Thanks to Professor Pierre-Alain Croset for his critical notes in this area.

2 Keunecke, D. and P. Niemz. "Axial stiffness and selected structural properties of yew and spruce micro-tensile specimens." *Wood Research,* 53, 1–14, 2008.

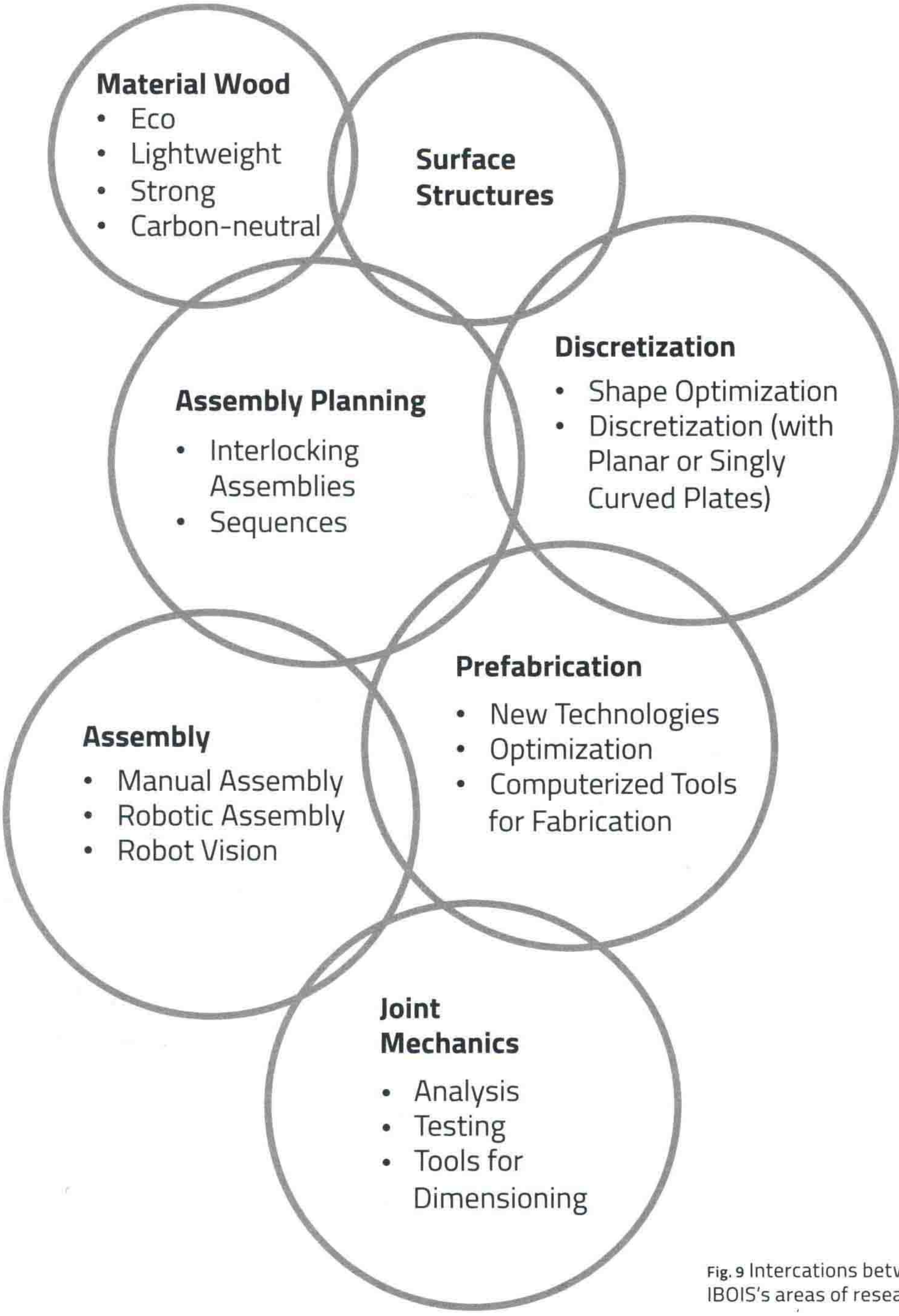


Fig. 9 Intercations between IBOIS's areas of research

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