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Timber Construction
Constructions en bois
Ingenieurholzbau

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SUMMARY

The paper gives a brief outline of wood-based construction materials and elements. Besides sawn lumber, glued laminated timber, which allows economical solutions also for long spans, is becoming widely used. The great importance of connectors in the optimum utilization of wood for structural purposes is pointed out. For structural sheathing, plywood offers excellent properties. A few examples show the possibilities of wood and its derivatives.

RÉSUMÉ

L'article donne un aperçu sur l'application du bois et de ses dérivés comme matériau de construction. Outre le bois scié, on utilise de plus en plus du bois lamellé-collé, ce qui permet de couvrir économiquement même des grandes portées. On montre aussi que le rendement des qualités mécaniques du bois dépend largement des moyens d'assemblage mis en œuvre. Pour les éléments porteurs plans, le contreplaqué se prête parfaitement. Quelques exemples illustrent les possibilités du bois et de ses dérivés.

ZUSAMMENFASSUNG

Der Beitrag gibt eine Übersicht über die dem Ingenieur zur Verfügung stehenden, auf Holzbasis beruhenden Baustoffe und Tragelemente. Nebst dem Schnittholz steht heute das Brettschichtholz im Vordergrund, mit dem grosse und wirtschaftliche Überdeckungen möglich sind. Zugleich wird die grosse Bedeutung der Verbindungsmittel für eine optimale Ansnützung der Holzeigenschaften aufgezeigt. Für flächenhafte tragende Elemente eignet sich das Sperrholz vorzüglich. Einige Beispiele illustrieren die Leistungsfähigkeit des Holzes und der Holzwerkstoffe.



0. INTRODUCTION

A great variety of wood species and wood-based products - depending on the geographical area - are available to the civil engineer for the design of timber structures. The various species do not only have certain properties in common, but also show marked differences, which makes a general statement difficult. Hence, the careful selection of the wood species and of the manufactured wood-based material is decisive for any engineered timber construction.

Apart from logs, which can generally only be put to use in very specific cases - for instance for poles, piles, etc. - the civil engineer has the following choice:

- sawn lumber
- glued laminated timber
- veneer and lumber plywood
- particleboard and fiberboard

Substantial differences according to the wood species are of course not only found in sawn lumber, but also in the manufactured wood-based material. Only a thorough knowledge of the properties of both will therefore lead to an economical and safe use of timber for structural purposes.

Most wood species have a very high strength and stiffness in proportion to their weight; parallel to grain, the properties of wood are comparable to those of high-strength steels of the type Fe 510, for instance (strength 510 N/mm², yield point 355 N/mm²). This shows that wood and wood-based products are building materials of highest quality which, if used in the right way, lend themselves well for large structures.

In spite of the above, wood and wood-based products are often not taken into consideration as building materials for structural purposes by civil engineers. The following are their objections:

- anisotropy and inhomogeneity of the wood
- shrinkage and swelling (hygroscopical behaviour) and tendency to split
- limited durability in connection with moisture
- fire hazards

The existence of the above characteristics can and should not be denied. However, they must be rated in connection with the various possibilities of using timber. In fact, carefully selected and properly dried, wood represents a building material of guaranteed quality.

The limited durability of timber must not only be considered in relation to the possible lifetime, but also in relation to the required time of use of a structure. There are many structures made of building materials other than timber which, in spite of a higher durability due to these materials, have proved to have a considerably shorter lifetime. Maintenance is of greatest importance for all types of building structures. On the other hand, we know of a number of buildings which, in spite of a potentially long lifetime, have become useless because the purpose of their use has changed.

On account of the large cross-sections customary in timber construction nowadays, the fire resistance of unprotected wood is much higher than that of comparable unprotected metal structures. Today, the inflammability of building materials

is being regarded as part-risk only. Fire resistance and permanent damages after the fire are considered equally important.

1. STRUCTURES WITH SAWN LUMBER

1.1 Development of new fastening systems

The need for reliable, simple methods of fastening with high efficiency is still one of the major problems in the application of sawn lumber. The traditional construction with wood-to-wood connections using ring connectors, tooth-plate connectors, shear plates, bolts and nails leads to a waste of wood and to high labor costs. New developments in the field of mechanical jointing nowadays allow a better use of sawn lumber and, through highly efficient production techniques and machinery, lower labor costs.

The following types of mechanical fastenings are presently in use for small and medium-sized structures:

- stamped connector plates
- multiple shear nail-systems
- spike plates

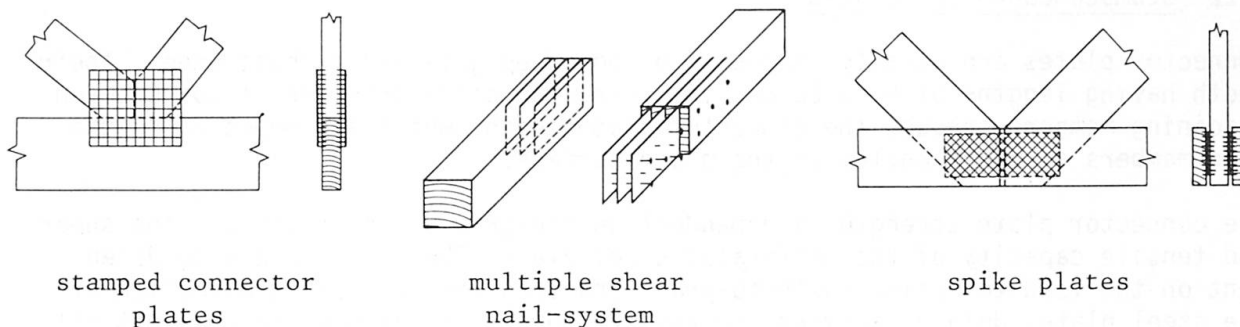


FIGURE 1

For light frame trusses, as for residential and agricultural constructions, the use of stamped connector plates keeps the manufacturing costs low and therefore leads to the most economical structures for medium-sized buildings.

For greater spans, multiple shear nail-systems or the Menig-spike plates are applied. The economical use of sawn lumber has therefore increased. Spans of 30 to 40 m for trusses have become normal. For trussed arches, even spans of 50 m and more are still economically feasible.

1.2 Range of application

1.21 General consideration

The different types of connectors are not interchangeable. Certain specific conditions have to be fulfilled:



Type of connector	Conditions of connecting members	Range of application	Working conditions
stamped	lumber of same width	only on the sides	simple shear serves as gusset ¹⁾
shear nail	lumber of different sections possible	no limitation (for nail-on plates same as for stamped plates)	multiple shear serves as gusset ²⁾
spikes	lumber of same width, splicing plate of wood or overlapping	only on the inner side	simple shear, wood has to transmit shear forces

1) Due to the perforation (stamping) and the thinness of the plates the gusset effect is limited

2) Only by using thick enough plates; otherwise the plates may buckle

TABLE 1

1.22 Stamped connector plates

Connector plates are usually stamped from hot deep galvanized sheet steel, their teeth having lengths of 6 to 22 mm. The connector plate transfers loads between adjoining members through the connector plate teeth, which are embedded in the wood members at right angles to the plate surface.

The connector plate strength is dependent on the grip of the teeth and the shear and tensile capacity of the perforated steel plate. The values are also dependent on the load-to-grain, tooth-to-grain and load-to-perforation direction of the steel plate. Joints carrying compressive forces are assumed to transmit all the compressive forces through wood-to-wood compression. An interesting study on the connector plate strength is given in [1].

1.23 Shear nail systems

Nail-on plates have the same range of application as stamped plates, but due to the higher labor costs involved (nailing instead of mechanized pressing), they are only being used in special constructions or for on-site connections.

Of greater importance are the multiple-shear-plates. Not only do they allow the use of lumber of varying size in one joint (therefore use of optimal sizes), but due to the multiple shear, the number of nails and the length of the connections can also be reduced.

The various types can be distinguished as listed below (see Table 2). Type A has found the widest application, although the use of plates of 1 mm thickness only is problematic. Type C leads to a high efficiency, but also involves the highest costs (drilling of the holes has to be done on the preassembled construction element). Through adequate mechanical drilling and nailing procedures, system B combines the advantages of system C (high specific loads) with those of system A (low costs).

Type	Drilling of holes	Application	Comment
A	wood and steel plate nailed without drilling	frequent (Greim, VB-system)	use of thin plates; limited length of cut
B	only wood drilled before nailing	rare (Blumer)	by special nailing use of 2 mm plates possible
C	wood and steel plate drilled together before nailing	without restriction	use of thick plates possible

TABLE 2

1.24 Spike plates

The small, densely disposed spikes of the Menig plates transfer the forces from wood to wood, which means that an overlapping of the connecting elements or the use of splicing plates of wood is necessary. In the case of trusses, excentric jointing is usual. The system is therefore better suitable for truss systems with small forces in the diagonals.

Larger sections have to be subdivided for a sufficient number of shear planes to be obtained. With the use of multiple chords and diagonals, long-span structures are possible.

1.3 Typical applications

The following pictures clearly show the differences in construction imposed by the type of fastening used.

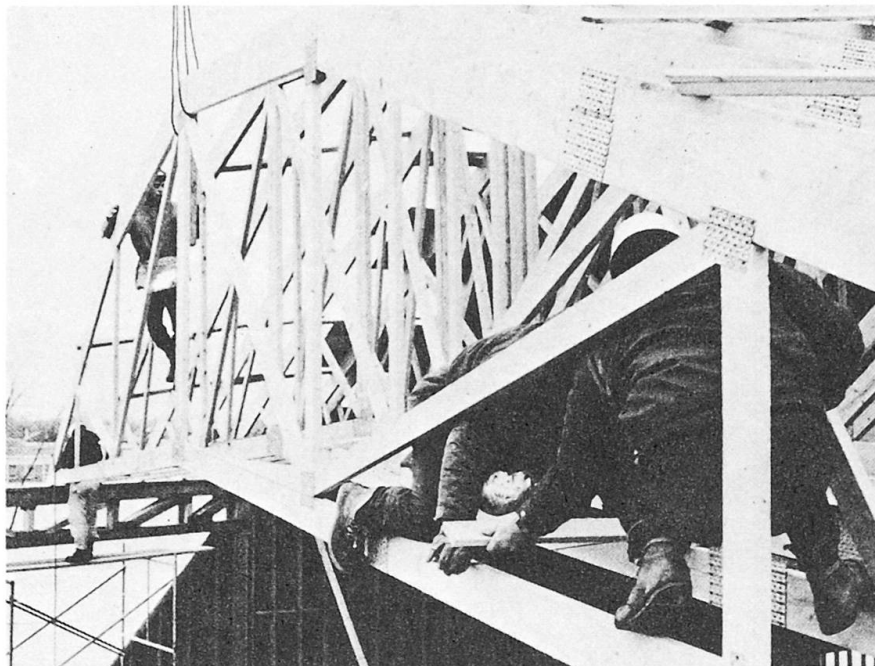


FIGURE 2



The individual sections are of limited size and formed of boards or planks. The small width of the elements results in a low lateral rigidity with a need for frequent lateral bracing.

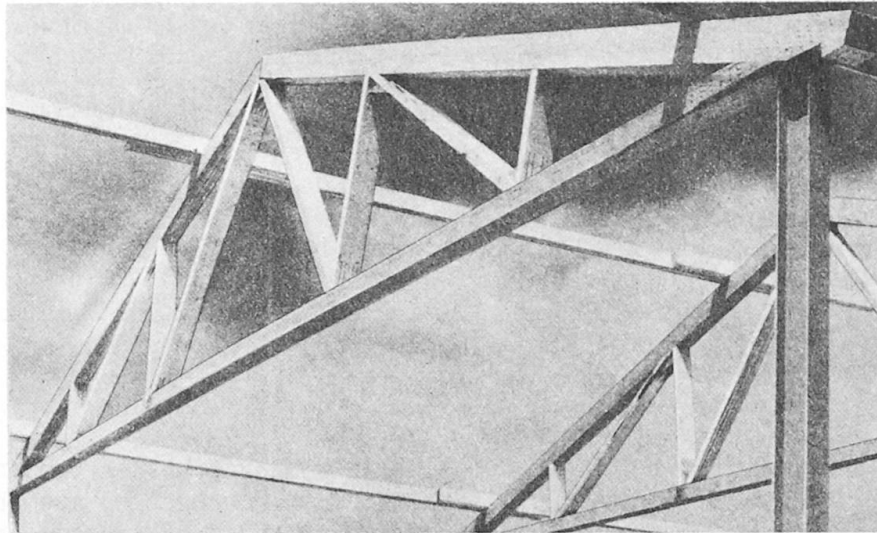


FIGURE 3

With the use of multiple shear nail-systems, the chords and also the diagonals may be of larger size. The greater width of the chords results in a higher lateral rigidity. Because of the larger individual sections, this type of construction requires a minimum of bracing and leads to greater distances between the girders.

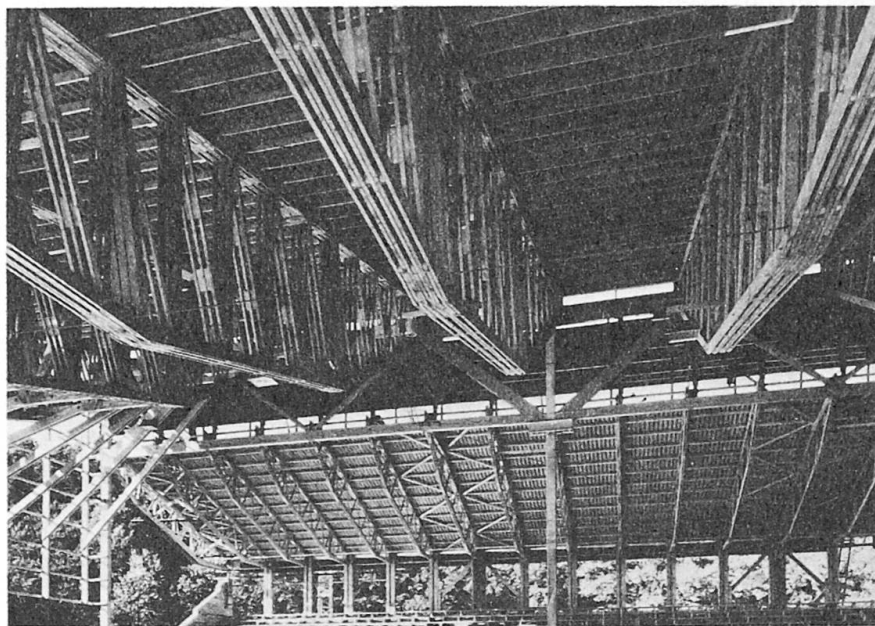


FIGURE 4

The use of the Menig spike plates for a large truss leads to a multiple chord and diagonal construction.



1.4 Special structures with sawn lumber

In space structures, such as lattice vaults, lattice shells, etc., sawn lumber of small dimensions can be used for large roof structures. Besides traditional methods of construction - such as the segmental arch -, lattice shell structures of any chosen shape, with double curvature, are becoming more and more predominant today [2]. The lattice shell roof of the Bundesgartenschau Mannheim (Germany) with spans up to 60 m is a classical example of the possibilities offered by sawn timber (lattice of two layers with a mesh width of 50 by 50 cm and single solid sections of 5 by 5 cm) [3].

2. LAMINATED TIMBER STRUCTURES

2.1 General

It is mainly due to the glulam elements that timber is being more widely used again in large structures. Glulam elements are built up of boards by gluing, the size of the elements being usually determined by the means of transportation available. Their easy shaping into curved plane elements has furthered the application of arch construction for spans of more than 100 m.

For glulam elements, the following species of softwood are given preference: in Europe above all withewood, and in smaller quantities redwood and douglas fir; in the USA douglas fir, southern pine and redwood, and in smaller quantities larch. Occasionally, also other species of softwood as well as hardwood are being used.

Through gluing and proper selection and arrangement of the laminations, the quality of the timber element can be considerably increased. This allows an economical use of laminations of varying quality.

Basically, glulam elements possess all the good qualities of sawn timber, especially also the exceptionally high strength parallel to grain. In addition, a restricted scatter of the mechanical properties is achieved, which allows a better utilization. Hardly any or no improvement at all on sawn timber is being attained by lamination as far as compression and tension strength perpendicular to grain or shear strength are concerned. The allowable stresses are somewhat higher than for sawn timber, only due to a reduced tendency to crack (cracks due to shrinkage). As a result of the industrial production of glulam elements, which is taking place under controlled conditions, the civil engineer has a wood-based material of reliable and guaranteed quality at his disposal.

2.2 Gluing

At present, gluing of structural members is exclusively done by synthetic glues. The adhesive must be suited to the wood species, the manufacturing process and the later conditions of use (climatic conditions, planned preservation processes, etc.).

2.3 Jointing of glulam elements

Most of the structures made of glulam elements are designed as statically determined systems, a fact which is mainly due to erection conditions, but also to difficulties with joint formations on site. Moment resistant erection joints



with the usual mechanical fasteners are costly and do not allow a high joint efficiency.

A new type of connection developed in Canada for on-site connections of glulam elements is the "glulam rivet", a special type of nail applied through pre-drilled steel plates to provide a swaged fastening with unique characteristics [4]. Glulam rivets provide greater load transfer per unit contact area than any other wood fastener.

Glued joints of larger cross-sections are feasible from the technical point of view; because of higher requirements, however, this jointing method is still rather expensive at present. Finger joints of larger cross-sections have been carried out successfully on various occasions; they may lead to joint efficiencies of over 80 % [5].

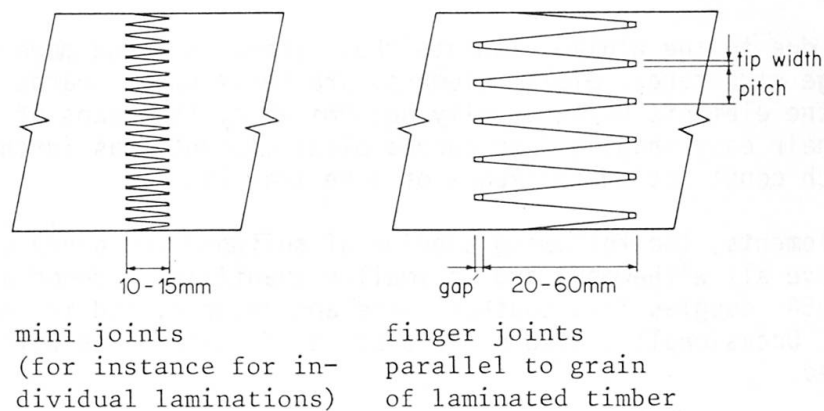


FIGURE 5

Besides joints parallel to grain, joints at an angle to grain are also often employed. Due to the lower resistance of the wood at an angle to grain, the forces that can be transmitted are also smaller, which results in a lower efficiency of the joint and of the jointed member.

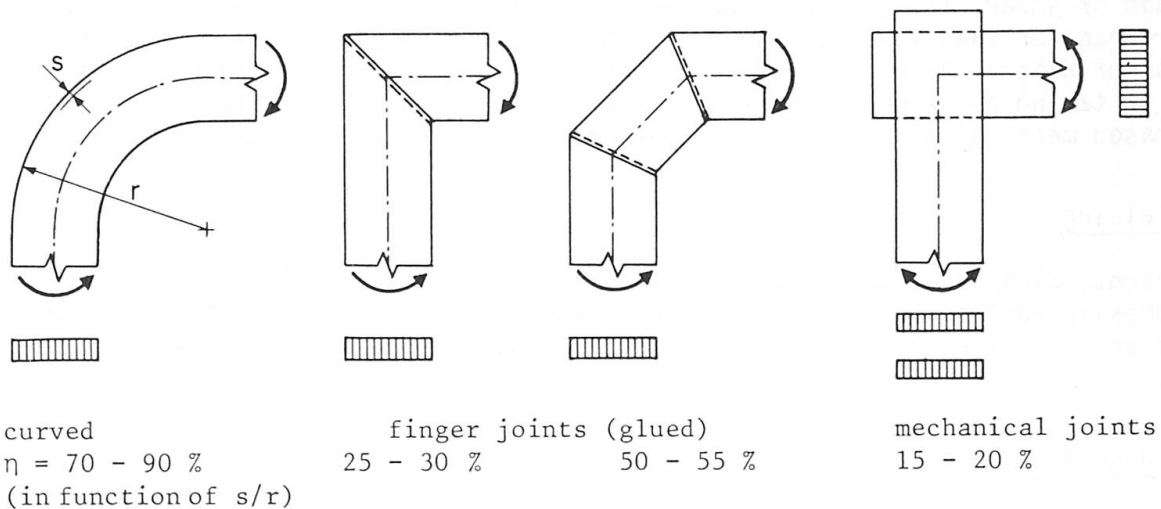


FIGURE 6

Efficiency of joints for a bending moment

2.4 Glulam elements of varying shape

Glued laminated elements are often tapered and/or curved to meet architectural requirements. In single or double tapered-straight elements the sawn taper cuts are not parallel to grain. Since the strength of wood at an angle to grain is reduced, tapered beams show smaller resistance. It is recommended that taper cuts be made on the compression side. The reduction of strength can be given through the Hankinson formula and can be seen in the graph below.

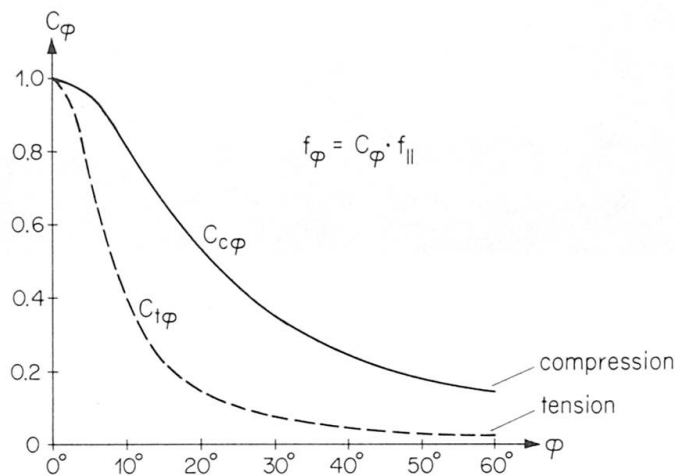


FIGURE 7

In curved elements subjected to a bending moment, radial stresses are set up in a direction perpendicular to grain. If the moment increases the radius of curvature, the stress is tension. In view of the small strength of wood perpendicular to grain, small radii of curvature are not allowed. Analytical methods taking into account the orthotropic behaviour of wood have been developed to determine the radial stresses [6],[7],[8]. The main problem lies now in an adequate formulation of the tension strength of wood perpendicular to grain in function of the wood species, climatic conditions and volume affected.

Another factor in curved elements to be considered are the stresses induced in bending laminations to the required curvature when fabricating the element. Existing formulas [9],[10] based on test results have shown a small influence. Recent studies show however that this influence has been underestimated [11].

2.5 Examples

The application of glulam elements is not limited to large structures. The use of glulam beams in residential and agricultural constructions offers many advantages. Nevertheless the covering of large areas is the most spectacular application. The secondary elements of these structures are usually of sawn lumber and attain about the same quantity in volume.

In the IABSE Publication C 6/78 - Recent Structures - the reader will find some interesting examples of glulam elements having been used for structural purposes. Two typical applications of glulam elements in arch construction can be seen on the next page.

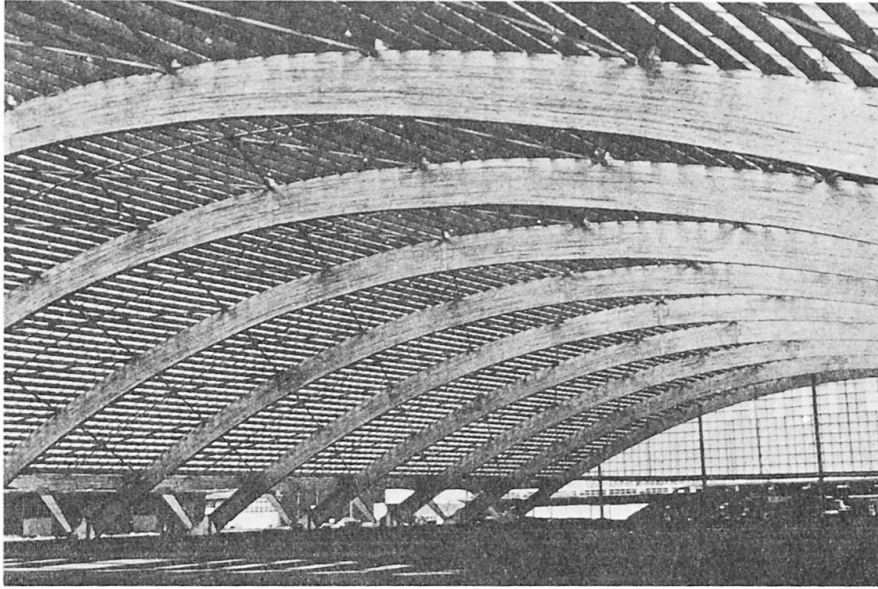


FIGURE 8

Covered market in Gent (Belgium)

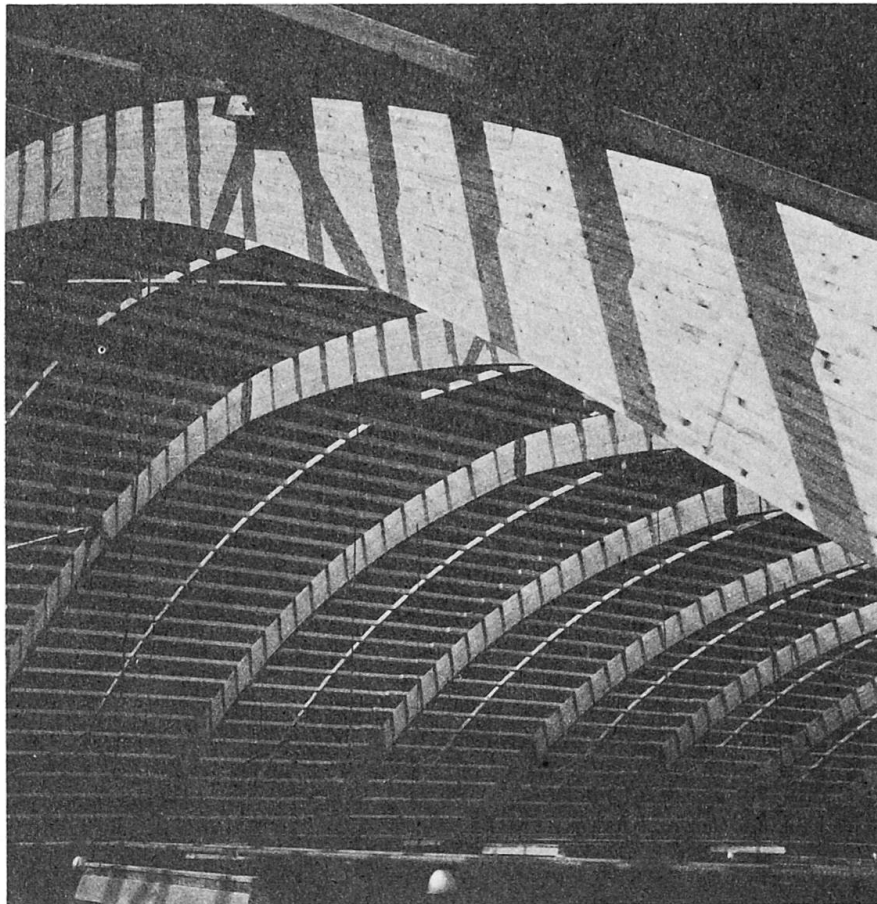


FIGURE 9

Ice-rink in Fribourg (Switzerland)

2.6 Glulam elements with laminations of veneer

Another possibility of manufacturing glulam elements lies in the use of veneer instead of boards. When veneer is being used, the single lamination does not have to be machined before gluing. On the other hand, there is a greater number of gluelines to be reckoned with. Until quite recent, the use of glulam elements with laminations of veneer was limited to a few special cases. However, for the construction of the vault roof of the football stadium of Idaho University Moscow (USA) [12], which has a span of 122 m, glulam chords of 610 x 47,6 mm (with laminations of veneer of 3,17 mm thickness) were used on a large scale.

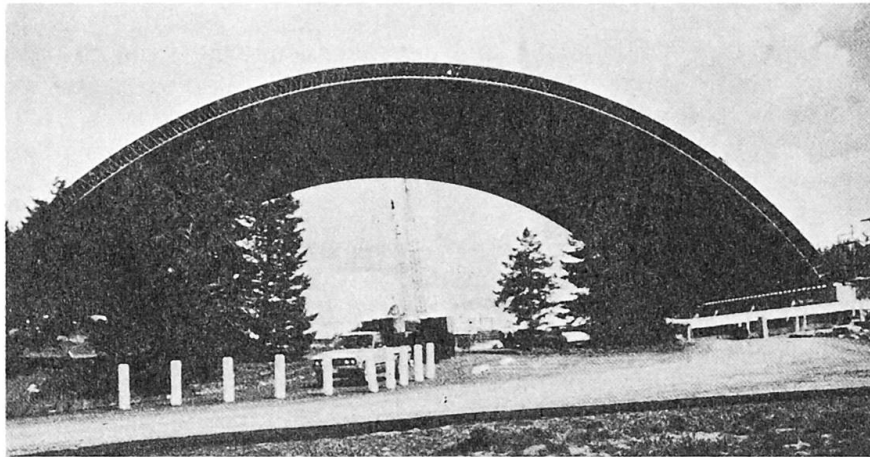


FIGURE 10

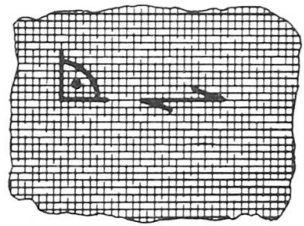
*Football stadium of Idaho University
covered with Truss-Deck-System*

3. VENEER AND LUMBER PLYWOOD

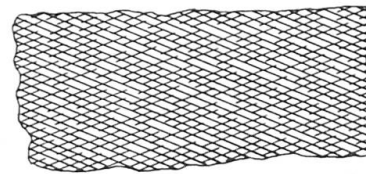
3.1 General

Veneer plywood and lumber plywood are a generalized form of laminated timber. Instead of the grains of all laminations or layers being parallel, the various layers or plies are arranged at angles, preferably at right angles. This arrangement results in a considerable improvement of the mechanical properties perpendicular to grain, however to the detriment of the properties parallel to grain.

A cross-banded assembly with a small angle between the layers hardly weakens the longitudinal properties, but notably improves the shear strength across the plane (e.g. in lumber plywood type Kämpf).



normal perpendicular
arrangement of plies
of veneer



small angle
between
directions
of grain

shear strength of lumber
plywood increased to almost
double the strength of lumber

FIGURE 11

Plates of more uniform properties in all directions may be obtained by a radial arrangement of the layers (e.g. neighbouring layers with angles of 45° or 30°). However, they are of little importance for structural purposes.

The mechanical properties of plywood are dependent on the kind of wood species, the composition of the plywood (thickness, number of layers, maybe different types of wood) and on the adhesive. If the mechanical properties of the various layers are known, most of the final mechanical properties of the plywood can be deduced from them with sufficient accuracy.

Plywood can be extensively used for floor, wall and roof sheathing, and exterior wall siding. It is also often used in beams as web (ply web beams).

An appropriate combination of plywood with sawn timber and glulam sections leads to economical solutions requiring a small amount of wood.

3.2 Jointing of plywood

For large structures, the plywood has to be jointed. Overlap joints or joints with splice plates are unsuitable. Scarf joints may be applied for thin plywood plates up to about 15 mm. For greater thicknesses and for lumber plywood, finger jointing may be considered, whereby the dimensions of the fingers have to be carefully adapted to the composition of the plywood. Adjoining plates have to be identical in composition and grain orientation.

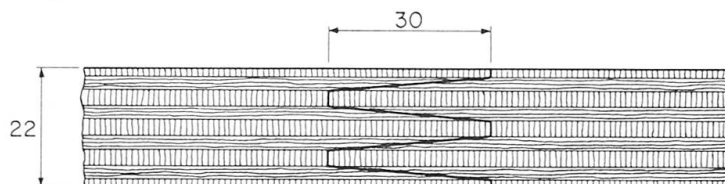


FIGURE 12

Plywood may be attached to lumber with adhesives or mechanical fasteners such as nails, screws, staples and bolts. Ultimate shear loads are available on nails, staples and bolts [13],[14],[15].



3.3 Typical applications of plywood

3.31 Plywood roof, wall and floor systems

Although the engineer can expect plywood floor, wall and roof sheathing to provide resistance to wind and earthquake forces in normal building connections, specific capabilities can be designed into these systems by utilizing the "diaphragm design" concept [16]. This concept assumes that horizontal loads are carried by roof and/or floor areas acting as deep beams. In roof diaphragms, the roof sheathing resists shear stresses, and building side-wall top plates are designed as flange members carrying tensile and compressive stresses. Building end walls are designed as "shear walls", or cantilevered diaphragms anchored to the foundation.

Shop fabricated componentized floor, wall and roof systems may be developed from available design methods [17],[18],[19],[20].

Walls may also be designed as deep plywood girders to provide stiffness and strength for applications such as sectional housing units that are to be transported to a building site, then lifted into place. Although an all-nailed plywood beam analogy can be considered for rough initial design approximations, door and window openings complicate deflection predictions with this approach [21].

3.32 Folded plates

The basic "deep beam" diaphragm design concept can also be applied for pitched roof systems, which may be treated as "folded plates" [22]. Folded plates may take on a wide range of configurations - trapezoidal, flat-top sawtooth, flat-bottom sawtooth profiles and others. The plates may be designed as stressed-skin panels combined to form diaphragms. Folded plates may be considered for spans up to 30 m.

3.33 Glued plywood-lumber elements

Plywood is commonly used as web element in ply web beams. For smaller elements the flange members are of sawn lumber or built up of only 2 laminations. The web may be straight or corrugated. In the latter case, flexure stresses are assumed to be carried only by the flanges.

The plywood webs are stressed primarily in shear through the thickness, but when glued, the flange-to-web shear stress (rolling shear) must also be checked.

Larger elements are constituted with glulam flange members. Where higher lateral stability is needed, for instance for arch elements, box sections may be an economical solution.

4. PARTICLEBOARD AND FIBERBOARD

Through decomposition of the wood into chips and fibres and subsequent pressing with adhesives, low-class timber such as waste materials from sawmills, weak logs, etc., can be turned into wood-based products of homogeneous quality. Plates fabricated from such products are of varying grades, depending on the type of wood, and are mainly used for partitionings and insulations.



The decomposition of wood into small particles leads to a loss of its natural qualities parallel to grain. Particleboard and fiberboard therefore have a low specific strength and their use in structural elements is restricted to special cases such as stress skin panels or structural diaphragms.

A relatively new product, largely unique to Canadian production, is waferboard: a specific type of flakeboard calling for certain special requirements for the constituent wafers and having special properties, distinct from other types of particleboard, that make a suitable alternative to plywood for many applications.

5. TIMBER AND WOOD-BASED PRODUCTS - MODERN BUILDING MATERIALS

In certain fields, timber has been almost completely superseded by reinforced concrete or structural steel. As far as the technical and economical advantages offered by concrete and steel structures are responsible for this take-over, it has to be accepted. Unfortunately, however, it is a fact that one of the main reasons for timber being left aside is the unwillingness of many engineers to deal with this building material which is somewhat more complicated but also offers a very wide range of applications.

Thanks to a refined quality grading system for sawn lumber and to the production of wood-based materials of guaranteed quality, timber industries are now able to offer reliable building materials for structural engineering. Timber structures can actually be designed and computed with the same accuracy as comparable structures made of steel or reinforced concrete.

For protected structures, i.e. structures in which the timber is not directly exposed to climatic action, the problem of durability does not arise. In fact, in such structures, if correctly designed, executed and maintained, timber may have a lifetime exceeding the time of service of the building. For timber used externally, on the other hand, the question of durability is of importance. There are marked differences between the various species of wood as far as their natural durability is concerned. The natural durability may however be greatly enhanced by appropriate processing (protection against climatic action). Many still existing unprotected old buildings confirm that the lifetime of wooden structures is far beyond expectation if basic provisions for the protection and conservation of the timber are made.

From the technical point of view, there is a wide range of possibilities of using timber for structural purposes, not exclusively, but in technically and economically optimum combinations with other building materials.

6. FUTURE DEVELOPMENTS

The potentials of timber and wood-based products for engineering structures have by far not been exhausted yet. A thorough study of the characteristics of timber construction by scientists, teachers, authorities and engineers might yield positive results from the technical as well as from the economical point of view. The problem of how to arrive at the technically and economically best building material or the optimum combination of materials still needs further consideration.



For future developments in timber construction, the following will be of significance:

- increased application of engineering methods and concepts in the design of timber structures, combined with a better utilization of timber and wood-based products
- application of the present know-how to species of wood which have either been insufficiently or unsuitably used so far
- economic feasibility studies to give more consideration to combined structural systems
- further development of protective measures to increase the natural durability of timber, especially for external use
- outdated rules and regulations for fire protection to be brought up to date
- preservation of forests through controlled wood-harvesting

The natural development of the existing forests still gives room for a considerable increase in wood production; timber therefore has a solid basis of raw materials. However, since forest resources are not unlimited, harvested wood should always be utilized to the last. This can be achieved by a well-balanced application of sawn lumber and of wood-based products.

The fact that timber, as compared with other building materials, consumes little energy both in production and processing will no doubt have a positive effect on its future.

7. ACKNOWLEDGEMENTS

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