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## DETERMINANTS OF SHAPING AN ARCHITECTURAL FORM AND STRUCTURE IN WOODEN HALLS

### UWARUNKOWANIA KSZTAŁTOWANIA FORMY ARCHYTEKTONICZNEJ I KONSTRUKCJI OBIEKTÓW HAŁOWYCH Z DREWNA

#### Abstract

In the paper, objects of modern hall construction of wood and mixed construction of primary structural systems are presented. Plane beam structures as well as trusses, post-and-beam construction, frame and arch construction are described in this paper. Cross-sectional dimensions and maximum span are estimated as well as information on the slope of roof surface is presented for the respective structural systems. The possibilities, restrictions and problems in shaping of architectural forms of the objects' structural systems also are presented in the paper.

*Keywords: glued laminated timber, glulam, transport limitations, girders, frames, arches, hall*

#### Streszczenie

W artykule omówiono obiekty nowoczesnego budownictwa halowego z drewna oraz rozwiązania mieszane o podstawowych układach konstrukcyjnych. Zaprezentowano płaskie ustroje belkowe i kratowe, słupowo-ryglowe, ramowe oraz łukowe. Dla odpowiednich układów konstrukcyjnych przedstawiono orientacyjne wysokości przekroju poprzecznego i maksymalne rozpiętości, a także informacje o pochyleniu połaci dachowej możliwej do osiągnięcia. Przedstawiono możliwości oraz ograniczenia i problemy, jakie należy uwzględnić w kształtowaniu form architektonicznych obiektów, ich układów konstrukcyjnych.

*Słowa kluczowe: drewno klejone, ograniczenia transportowe, dźwigary, ramy, łuki, hala*

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## 1. Introduction

The first patents for glued-laminated timber (glulam) were issued more than a hundred years ago; however, Polish experience with this material is still quite poor. The use of this material in practice is restricted mainly to hall buildings functioning as sport, factory or sacral buildings.

In the era of modern emphasis on protecting the environment, wood is presently becoming the pivotal building material. The favorable ratio of the weight of timber to its stiffness and strength makes it possible to carry out the project with wide-span structures. Investors are choosing glulam more and more often as a solution, which at the same time gives the impression of being similar to solid wood. Moreover, it gives “psychological comfort” by introducing an warm and natural atmosphere to the object and its visual elegance and high aesthetic values of structure does not require additional finishing work. Timber is the material for which architects eagerly reach for as it allows for the realization of their creativity and imagination. Thus, the huge potential hidden in wood enables them to fulfill a wide variety of projects requiring uncommon and sophisticated ideas. In spite of this, the restrictions concerning the possibilities of shaping different forms of construction should be taken into account.

This publication is limited to give the characteristic features of the typical hall construction, most commonly observed in Poland, consisting of flat bearing systems placed perpendicularly to the longitudinal axis of the building.

## 2. Construction systems of a wooden hall

The classification of the glued-laminated timber with respect to the shaping of forms was made by Professor Wiesław Rokicki in [1]. Hall architecture, considered as the most typical and characterized by simple geometrical relations, has been placed as the primary construction of classification. It is implemented most frequently as a plane structural system such as: beam, truss, post-and-beam, frame and arch construction.

### 2.1. Plane structural system

The most frequently used flat systems with respect to the distance between particular flat systems (trusses, frames and arches) of about 4–10 m were presented in tables 1–5. Cross-sectional dimensions, economical and maximum span were estimated as well as information on the slope of roof surface was presented.

#### *2.1.1. Structural systems of beam and truss*

Structural systems of beam and truss are implemented as triple-hinged systems, consisting of two beams or trusses very often supported by a steel brace. The use of a brace is usually essential when the height of construction is lower than  $1/3$  of its span.

Table 1

## Beam and truss structures [4]

|   |             |                 |   |
|---|-------------|-----------------|---|
| $L$ [m]   | $H$         | $\alpha$ [°]    | Three-hinged structure, consists of two beams   |
| without brace<br>15 ÷ 30 (maximum span 45 m)<br>with brace<br>15 ÷ 40 (maximum span 50 m)                     | $\sim L/30$ | $\geq 14^\circ$ |   |
| $L$ [m]   | $H$         | $\alpha$ [°]    | three-hinged structure, consists of two trusses |
| without brace<br>15 ÷ 30 (maximum span 45 m)<br>with brace<br>15 ÷ 40 (maximum span 60 m)                     | $\sim L/20$ | $\geq 14^\circ$ |   |
| where:<br>$L$ – the span of the structure<br>$H$ – the depth of the member<br>$\alpha$ – the roof pitch angle |             |                 |   |

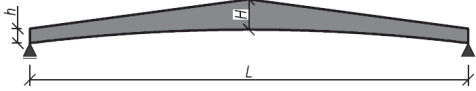

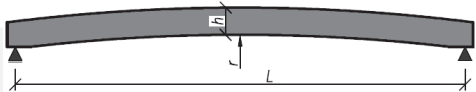
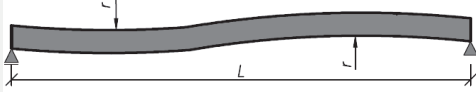
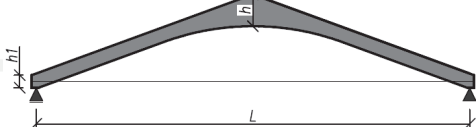
## 2.1.2. Post-and-beam constructions

They are most frequently used as construction of beam and truss girder. Constructions of this type can be implemented as mixed systems; glulam girders are based on steel or reinforced concrete columns, or masonry, concrete and reinforced concrete walls.

Table 2

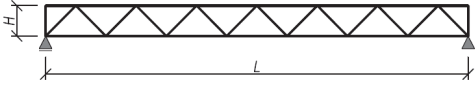
## Post-and-beam constructions (beam girder of rectangular cross-section) [4, 5]

|   |             |                |                            |                            |
|---|-------------|----------------|----------------------------|----------------------------|
| Rectangular cross-section constant over the entire length of the beam |             |                |                            |                            |
| $L$ [m]   | $H$         | $\alpha$ [°]   | <b>with edges parallel</b> |                            |
| < 30  | $\sim L/17$ | $\geq 3^\circ$ |                            |                            |
| Rectangular cross-section linearly variable along the beam length     |             |                |                            |                            |
| $L$ [m]   | $H$         | $h$            | $\alpha$ [°]               | <b>single tapered beam</b> |
| 10 ÷ 35   | $\sim L/16$ | $\sim L/30$    | 5 ÷ 12°                    |                            |
| $L$ [m]   | $H$         | $h$            | $\alpha$ [°]               | <b>double tapered beam</b> |
| 10 ÷ 30   | $\sim L/16$ | $\sim L/30$    | 3 ÷ 10°                    |                            |

| Beams with a curved lower edge and a variable cross sectional height |             |              |              |  |
|--|-------------|--------------|--------------|--|
| $L$ [m]  | $H$         | $h$          | $\alpha$ [°] | <b>Double tapered pitched cambered beams „boomerang”</b>                             |
| 10÷20  | $\sim L/16$ | $\sim L/30$  | 3÷15°        |    |
| $L$ [m]  | $H$         | $h$          |              | <b>„fish belly”</b>  |
| 20÷35  | $\sim L/16$ | $\sim L/32$  |              |    |
| Curved beams with rectangular cross sections with constant height    |             |              |              |  |
| $L$ [m]  | $h$         | $r$ [m]      |              | <b>arch</b>  |
| 6÷30   | $\sim L/17$ | $\geq 7,5^*$ |              |    |
| $L$ [m]  | $h$         | $r$ [m]      |              | <b>beam type „S”</b>   |
| 6÷30   | $\sim L/17$ | $\geq 7,5^*$ |              |    |
| Bowstring girders  |             |              |              |  |
| $L$ [m]  | $H$         | $h$          | $\alpha$ [°] | <b>tie-beam „boomerang”</b>  |
| 10÷40  | $\sim L/14$ | $\sim L/34$  | $< 12^\circ$ |  |
| where:   |             |              |              |  |
| $L$ – the span of the structure                                      |             |              |              |  |
| $H, h$ – the depth of the member                                     |             |              |              |  |
| $\alpha$ – the roof pitch angle                                      |             |              |              |  |
| $r$ – the radius of curvature  |             |              |              |  |

Truss constructions can have different shapes. Currently, the ones which are most frequently used are timber and steel trusses, which give the effect of visual lightness of construction.

**Post-and-beam constructions (truss girders) [4]**

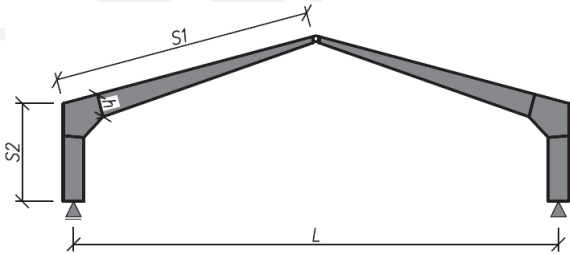
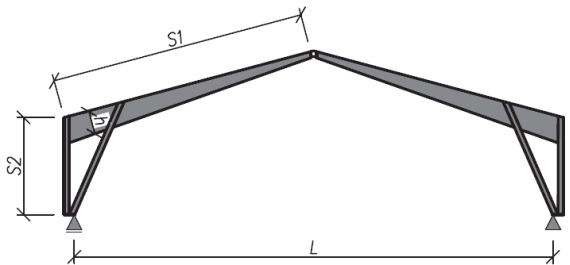
| Truss girders   |             |                |  |
|---|-------------|----------------|--|
| $L$ [m]   | $H$         | $\alpha$ [°]   | truss of parallel booms  |
| 30÷85   | $\sim L/14$ | $\geq 3^\circ$ |  |
| where:<br>$L$ – the span of the structure<br>$H$ – overall rise of the truss<br>$\alpha$ – the roof pitch angle |             |                |  |

*2.1.3. Frame and arch constructions*

Due to the importance of the static scheme, we can distinguish between frames and arches: hingeless, single-hinged, double-hinged and triple-hinged in the ridge. The most commonly used are triple-hinged systems usually made of two elements connected by hinges in the ridge. Arches can be constructed in any shape; however, architects usually make it in the shape of a parabola.

Table 4

**Frames [4]**

| Triple-hinged frames |                     |                 |  |
|----------------------|---------------------|-----------------|--|
| $L$ [m]              | $h$                 | $\alpha$ [°]    |  |
| 15÷25                | $\sim (S1 + S2)/13$ | $\geq 14^\circ$ |  |
| 10÷35                | $\sim (S1 + S2)/15$ | $\geq 14^\circ$ |  |

|   |                    |                 |  |
|---|--------------------|-----------------|--|
| 15÷50   | $\sim(S1 + S2)/15$ | $\geq 14^\circ$ |  |
| <p>where:</p> <p><math>L</math> – the span of the structure</p> <p><math>h</math> – the depth of the member</p> <p><math>\alpha</math> – the roof pitch angle</p> |                    |                 |  |

Table 5

**Arches [4]**

| Arches with solid rectangular cross section  |               |                |   |
|--|---------------|----------------|---|
| $L$ [m]  | $H$           | $f$            | <b>double-hinged arch</b>                       |
| 30÷100   | $\sim 0.025L$ | $\sim L/0.125$ |   |
| $L$ [m]  | $H$           | $f$            | <b>triple-hinged arch</b>                       |
| 20÷100   | $\sim 0.025L$ | $\sim L/0.17$  |   |
| Truss arches   |               |                |   |
| $L$ [m]  | $H$           | $f$            | <b>hingeless , double-hinged, triple-hinged</b> |
| 50÷120   | $\sim 0,035L$ | $\sim L/0,16$  |   |
| <p>where:</p> <p><math>L</math> – the span of the structure</p> <p><math>H</math> – the depth of the member</p> <p><math>f</math> – the rise of the arch</p> |               |                |   |

### 3. Possibilities and restrictions

The development of technology in the area of timber constructions, the invention of combining techniques and special water-proof glues on the basis of resin have made it possible to cross the biggest boundaries which had restrained the development of solid wood architecture. The length and thickness of tree bole is not a problem; however, the restrictions concerning the technological and production possibilities as well as transportation seem to be very important limiting factors. Quality restrictions are also very important, most manufactures have no technical approval to produce glulam elements above GL28h.

Polish manufacturers of glulam are still limited by production and technological restrictions caused by the excessively small capacity of machines and tools used in manufacture. Thus, Polish producers in comparison with manufacturers from abroad seem to have a rather poor record in terms of the length of elements offered by them as well as their capacity of manufacturing curved elements. Contractors very often import construction elements made of glulam from foreign manufacturers who are capable of making even 60 meter long elements. Moreover, the bending radii they achieve reach even 2 meters (for the thickness of 8 mm lamellae). Taking that into consideration, we assume that the key restriction for timber construction is the problem of transport. The longest girders transported across Poland are not usually longer than 45 meters. It must be remembered that transport with oversized vehicles is related to the necessity to obtain essential permits for transit, and the use of special tools and the use of special transportation, and if the length of the element exceeds 23 m, even pilot transit is necessary [3]. Not including transportation limitations at the stage of the project and at the same time designing oversized elements may hinder or even make it impossible to transport them which could result in the necessity of redesigning of the whole project.

For frame and arch systems, an important limiting factor is the width of the transport vehicle, these structures are usually implemented as triple-hinged and delivered to the construction site usually in two elements. Designing an arch that is not soaring or a girder of an overly small slope, can be the reason for significant transportation problems. The solution to transport problems of frame structures can involve designing of a stiff joint of the frame as connections can be implemented on the building site.

Transportation problems concern mainly solid-web elements. If the restriction does not allow for the use of solid-web construction, the solution to the problem may be the truss system. Such constructions can be supplied to the building site in segments. If the visual effect is not satisfactory, the truss can be finished (rimmed) by panels of glulam which give the effect of a solid beam. Obviously, because of aiming at maximal prefabrication of elements, the time of assembling and possible faults in constructing are reduced. However, we have to take into account the condition of Polish roads as it happens very often that transportation of oversized construction elements to small towns is impossible.

What seems to be a crucial limitation for shaping glued-laminated timber elements is the capability of bending. Despite the fact that production of bent elements in two or more dimensions is possible, this process is technically complex and expensive [2]. Usually, bending is performed in the vertical plane of the element. The most frequently implemented are elements of a similar curvature along the entire length, apart from those elements where the bending radius at the length of the beam is variable or partly curved and partly linear. The possibilities of shaping forms of structural elements are additionally limited by the value

of the minimum bend radius. The bending radius should not be too small in relation to the thickness of the lamella in order to reduce stress in the timber. The standard thickness for the lamella in glulam beams is 40 mm; the arched beams are made of timber with a thickness of 33 1/3 mm – for such thickness of the lamellas, the minimum radius, which it is possible to obtain, is 6 m. For smaller radius of bend, accordingly thinner timber should be used, which greatly increases the cost of production and the price of the final product; therefore, mainly elements of standard bend radius are produced.

#### 4. Conclusions

The possibilities of shaping forms of glued laminated timber are huge. Manufacturers or suppliers offering glued laminated timber, provide almost unlimited opportunities in shaping timber elements [6–9]. However, each architect or designer, who implements the construction of glued laminated timber, especially large span, must be aware of existing restrictions in particular transport; also technological and production limitations are important. A relevant barrier to the implementation of the construction of custom elements, offered by manufacturers of timber are economic considerations. Production of elements of non-standard forms, for example, less than the standard range of bending radii, significantly increases the cost of production of these elements and thereby increasing the cost of the investment.

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