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ZOLLINGER LAMELLA VAULT OF EXISTING TIMBER HANGARS IN ŠIBENIK (CASE STUDY) – INITIAL CONDITION ASSESSMENT AND PRELIMINARY ANALYSIS OF GLOBAL STRUCTURAL FEATURES

Abstract

A preliminary condition assessment using non-destructive testing methods for determining material quality, has been carried out on three adjacent wooden hangars near Šibenik with the aim of exploring the possibilities of their repurposing. Through visual inspection and detailed geometric measurements, it has been verified that their unique structure embodies the original Zollinger lamella vault system in which the joint typology is decisive for both, the overarching structural analysis and the execution of the structure. In this paper, the results of conducted investigation, including the developed detailed geometric model are presented, and guidelines for future comprehensive research focusing on the influence of joint stiffness on global structural features are discussed, as well.

Keywords: timber, Zollinger lamella vault, on-site testing, results, guidelines for further analysis

ЗОЛИНГЕР МРЕЖАСТИ СВОД ДРВЕНИХ ХАНГАРА У ШИБЕНКУ (СТУДИЈА СЛУЧАЈА) – ПОЧЕТНА ОЦЈЕНА СТАЊА И ПРЕЛИМИНАРНА АНАЛИЗА КАРАКТЕРИСТИКА КОНСТРУКЦИЈЕ

Сажетак

За групу од три сусједна дрвена хангара код Шибеника извршена је прелиминарна процјена стања примјеном неразорhix тестова за одређивање квалитета материјала, како би се испитале могућности њихове пренамјене. На основу визуелног прегледа и детаљних геометријских мјерења је потврђено да јединствена конструкција јест оригинални Золингеров ламелни свод у коме је типологија споја кључна како за цјелокупну анализу конструкције тако и за њено извођење. У овом раду су приказани резултати спроведених истраживања, укључујући израду детаљног геометријског модела и дискутоване су смјернице за будућа детаљна истраживања, са фокусом на утицај крутости спојева на глобалне карактеристике конструкције.

Кључне ријечи: Золингер дрвени свод, теренскі тестови, резултати, смјернице за анализу

1. INTRODUCTION

This work is the result of preliminary investigation work carried out on three hangars with the aim of condition assessment of the structural timber elements. Although there are five hangars of the same structure at this site only three hangars (Figure 1), are planned to be repurposed as an educational facility dedicated to undersea biodiversity and integrated into the continuation of the project „Tourism Valorisation of the St Anthony's Channel“. The hangars are located in Minerska Cove (in suburb of Šibenik), directly opposite the St Nicholas’ Fortress, which was inscribed on the UNESCO World Heritage List in 2017. Until the 1990s, the hangars were part of a large military complex of the former army, and since then they have been abandoned and heavily devastated. Although there is no project documentation or other evidence of the real age of the buildings, it is possible that they were built during the Second World War for the needs of German military units and served as ammunition warehouses even then.

Figure 1. Three adjacent hangars (left) located in Minerska Cove (right) [1, 2]

Figure 2. Timber hangars – typological characteristics of diamond grid structure [1, 2]

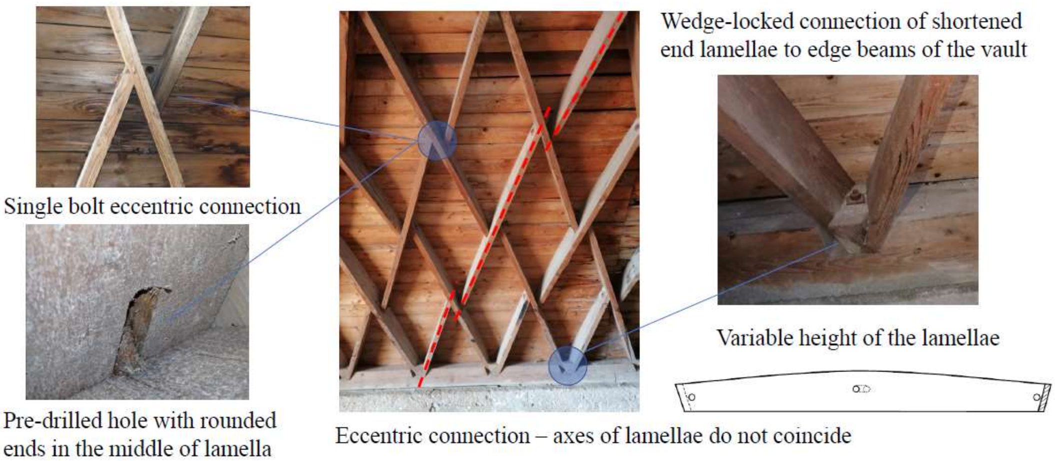
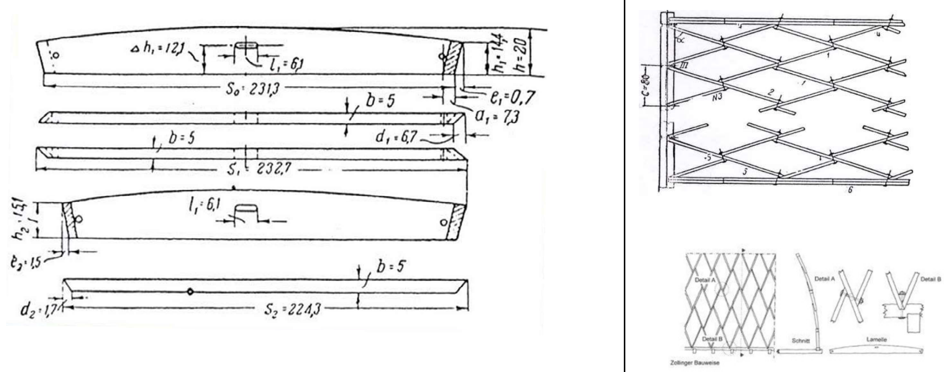


Figure 3. Lamellae and joints – similarity with Zollinger lamellar vault system [1, 2]

It is evident that the structures of all three hangars (Figures 2 and 3) embody the original Zollinger lamellar vault system patented in the 1920s (Figure 4). Faced with crisis in residential construction at the time, Friedrich Reinhart Baltasar Zollinger (appointed Town Building Advisor at Meresburg, Germany in 1918) developed the "Zollbau" method for flats and houses, based on the use of precast concrete panels and a timber sawing low form of gothic arched roof using "Zollbau Lamellen Dach" – system that he patented in 1921 [3, 4]. This work led him to develop the lamellar system for large spans (schools, churches and large halls), which he patented in 1923 and which became widely used for arched roofs in Europe and America. The basic idea of the structure comprised of a network of intersecting helices of thin planks (lamellae) of varying lengths forming diamond-shaped cells with bolted joints at their intersection [3, 5], as shown in Figure 4.



Lamella’s shaping depends on the geometry of vault and joint | Vault floor plan and details

Figure 4. Original Zollinger system of lamellar vault [6]

The conducted preliminary investigation work and the resulting report on the current state and timber members quality are the usual starting points for further actions - a detailed condition assessment of the existing structure as a basis for proposals for renovation measures or removal and replacement with a new one (Figure 5). As the analysed hangars are not under the protection as heritage objects, but the architectural value of their structure is recognised, the replacement option implies a facsimile of a similar typology that meets the current requirements for mechanical resistance and stability as well as fire resistance. Other necessary structural interventions must include the connection of the hangars to an external corridor and the integration of installations and equipment that meet reuse requirements. The investigation work included a visual inspection, detailed geometric measurements of the hangars and the structural elements available for inspection, and the implementation of non-destructive tests to determine the condition and quality of the timber lamellae.

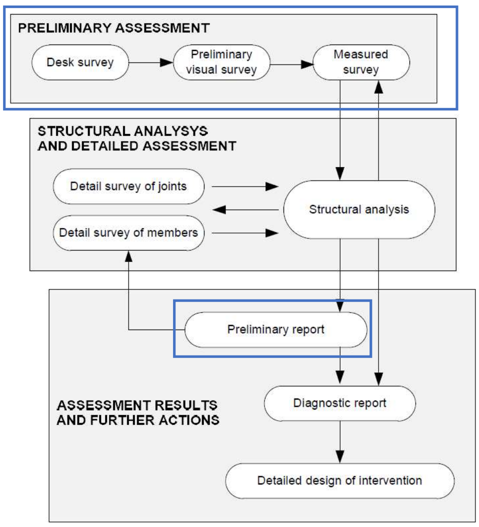


Figure 5. Different assessment phases and accompanying actions

This paper presents the results of the research work and the continuation of the research, which were prompted by the uniqueness of the structure's typology. A geometric model of the lamellar vault was created as the basis for the structural analysis and condition assessment of the existing structure. Since the type of joint - the eccentric bolt connection - is decisive for the evaluation of its behaviour, laboratory tests were also carried out to a limited extent on samples with approximately the same timber quality, connection geometry and bolts in order to check the suitability of the test settings and to gain an insight into the connection failure. A discussion of the preliminary laboratory test results is also part of this paper.

2. PRELIMINARY ASSESSMENT RESULTS

Investigation work on the hangars was carried out according to the valid regulations and standards as well as the existing guidelines for timber structures [7, 8, 9]. The activities did not include a global condition assessment of the structures nor proposals for interventions, and the prepared report will be a precursor to the preliminary design project for reuse (the structures are not architectural heritage) [2]. Only the condition of the structural elements was assessed and qualitative recommendations for further actions were given (Figure 5). The lack of project documentation was compensated by preparing a building blueprint (Figure 6). Although numerous and various methods and techniques are available on the market for the condition assessment of existing timber structures [10], the initial step is to select the appropriate methods for a specific case study (taking into account the parameters of the cost-benefit analysis). The final step is the implementation of the measured and estimated data into a model for structural analysis. The prepared preliminary report is therefore based on a visual inspection and detection of the botanical species and an inspection with the following measurements: geometry of the structure and structural elements, timber moisture content and dynamic modulus of elasticity. The selection of reference measurement points was based on a visual assessment – in each hangar, the elements with suspected and/or occurred significant degradations and available for inspection were selected (equipment for inspecting higher parts of the structure that would ensure the safety of the examiner was not available).

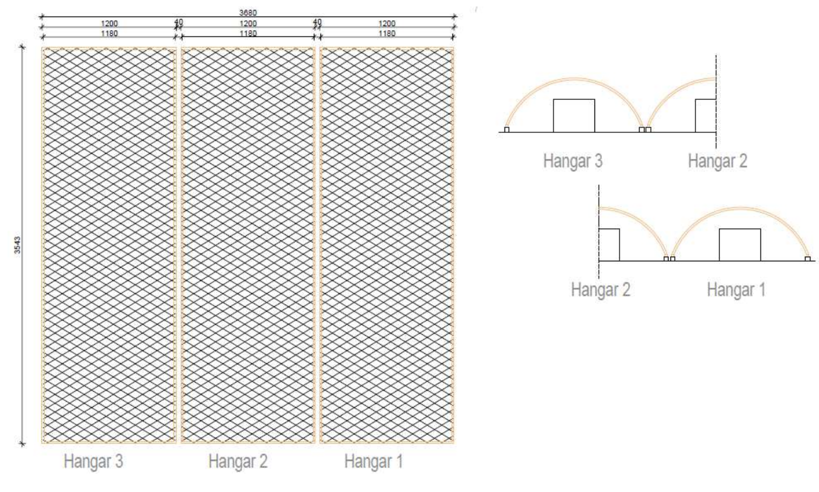


Figure 6. Timber hangars – floor plan and gables (view from sea side) [2]

2.2. VISUAL INSPECTION AND GEOMETRIC MEASUREMENT

A visual inspection confirmed the obvious consequences of years of neglect of the hangar. Apart from the fact that the covering made of curved asbestos-cement panels is not acceptable for any current use, localised damage to the covering (gaps in the areas of the panel joints) and the bitumen pasteboard has led to deterioration of the timber formwork and the visible consequences of its long-term wetting on significant areas of the vaults. Localised structural degradation of the edge base beams, which are anchored in low concrete walls, is also evident, particularly at the gables where the ends of the beams are protruding. Structural damage is also visible at the rarely accessible parts of the edge arches (they are two-part, bolted together from the lamellae and hidden by gable walls made of masonry blocks). The consequences of exposure to moisture are also visible on the timber lamellae of the vaults, with the discoloration (greying due to surface erosion) being more pronounced in the zones where they have also been exposed to the sun (the hangars have been without doors for years). Along the gables on the south-west side of Hangar 2 (the area at the base of the vault, along the gutter towards Hangar 3), the covering panels were completely destroyed, and the inevitable rotting zones of the timber structure were also detected there (lamellae, edge beams and arches). No significant mechanically induced damage to the lamellae were observed, although it does occur occasionally, albeit in negligible numbers. It can also be seen that some (e.g. along the entire length of one side of Hangar 3, the lower part of the vault) were caused by the removal (probably by pulling) of something when leaving the hangar. The consequences of the "work" of the connections are also visible in some areas – although the ends of the holes in the lamellae are rounded, damage around the holes was observed on a smaller number of lamellae in the lower sections of the vaults, regularly combined with degradation of the material due to wetting (areas with gaps between the covering boards). Longitudinal cracks on the connected lamellae (extending from the joint) are also observed. The lamellae are made of larch wood and are generally in good condition despite visible signs of ageing (the timber has hardened and undergone all rheological changes without significant dimensional changes) and aesthetic damage (discoloration). All anchors, bolts and washers have completely corroded. Results of the survey are shown on Figures 7, 8 and 9.

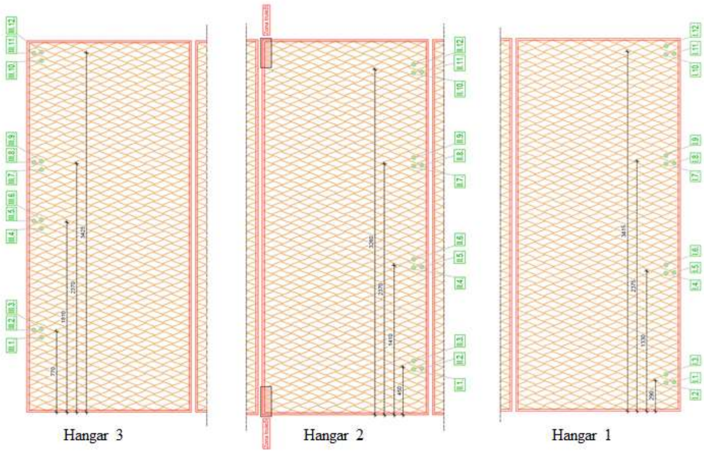
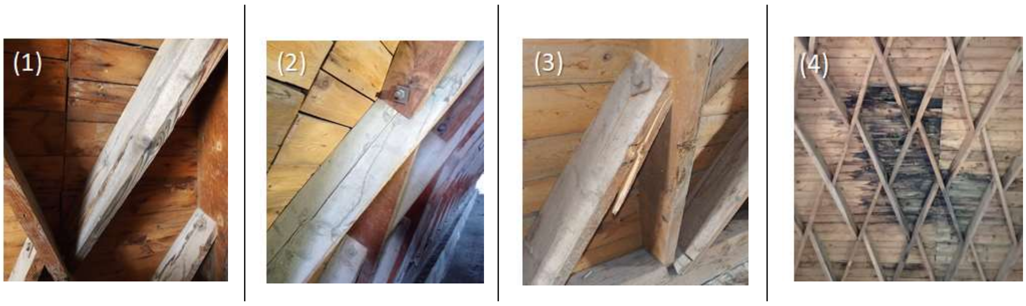


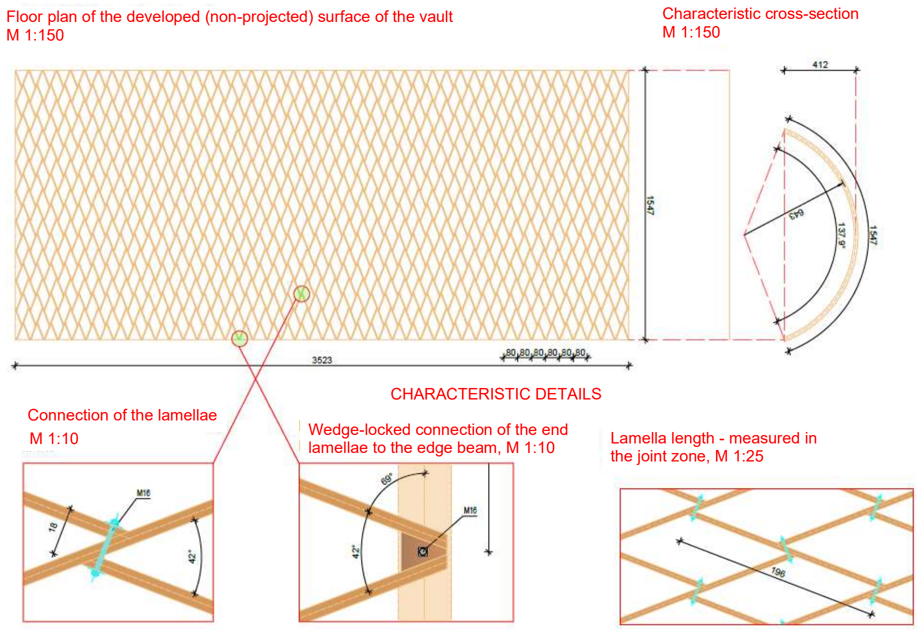
Figure 7. Probe positions and location of detected decay (dry rot) in Hangar 2 [2]



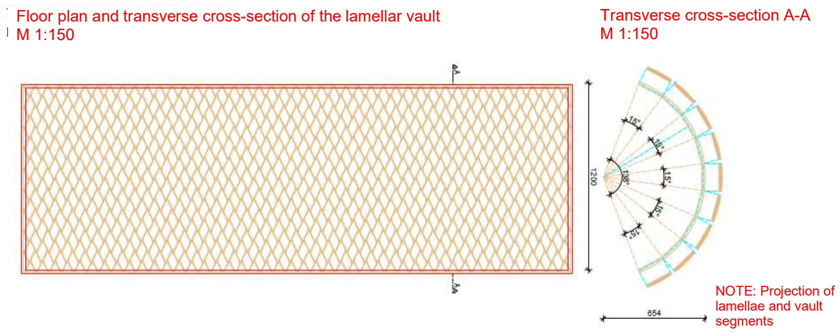
(1) Knots, grain irregularities, grey stains, (2) cracks, (3) mech. damages, (4) decay of the covering boards.

(5) Anchor corrosion and a piece of decayed edge beam (Hangar 2, zone of the northern gable), (6) damage in the vicinity of a hole (mechanical, but possible combined with decay – gap between covering planks is visible, (7) overall decay of timber (Hangar 2, zone of southern gable); Measured dimensions of lamellae (50 mm, width vary from 145 up to 225 mm), bolts and anchors diameter (M16).

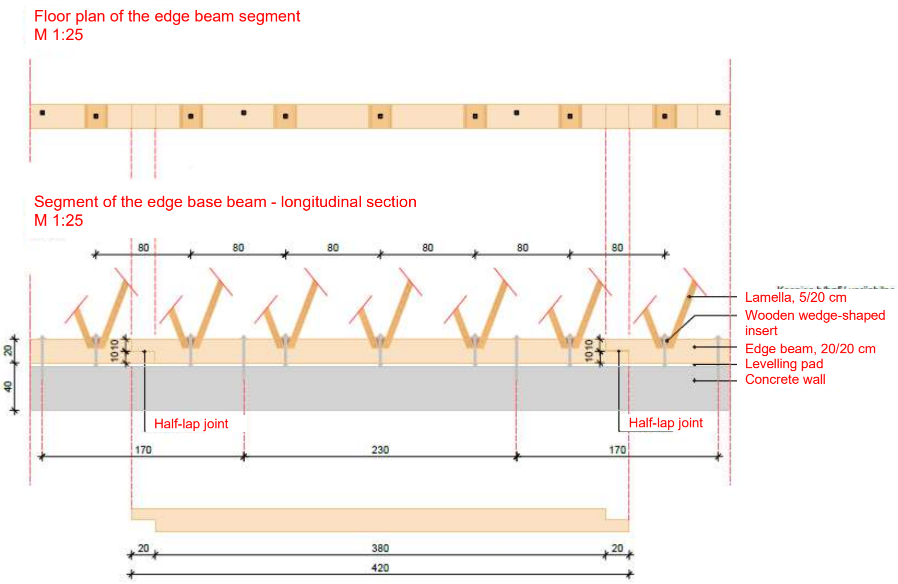
Figure 8. Observed damage types (brief overview) and measured dimensions [2]



Floor plan dimensions (diamond grid), height of the structure and essential geometric measured parameters



Projections: floor plan (grid: 44 x 0,8 m) and cross-section of the vault (division into 9 segments)



Edge beams – joining of adjacent segments in the queue and arrangement of anchoring in concrete wall

Figure 9. Drawings resulted from measured survey [2]

2.3. NDT SURVEY

The determination of load duration class and the service class according to the EN 1995-1-1:2004 standard [11] is based on the visual inspection of the timber structure and the measurement of the moisture content in the material. Together with the classification of the material into strength classes, in this way the necessary assumptions for the implementation of structural analysis are fulfilled. The following non-destructive tests (NDT) of the lamellae were carried out at the selected probe positions, which are shown in Figure 7. The probe positions included four characteristic areas in each hangar (two near the gables and two in the center), namely those for which the visual inspection indicated qualitatively different structural conditions. The measured average room temperature was 8.5°C and the relative humidity was 45.3%.

- Hygrometric test (using Brookhuis FMC / FME Moisture Meter for timber elements) – the purpose is to assess the influence of the moisture content of wood on its technical properties (the potential for the presence of rot) and to apply the results in the procedure of classification of lumber according to strength.
- Ultrasound test (using CBS-CBT SylvaTest TRIO portable ultrasonic device) – with indirect longitudinal test (dynamic MoE measurement), the lamellae were examined along parts of the length (outside joints zones and at the lower edge, at the same positions as for moisture content measurements), and with radial test, the presence of local rot was checked.

In the indirect longitudinal test, the paired probes were placed on the surface of the lamella (at a slight angle to the grains, much less than 30°). The probes are connected directly to the measuring devices with a cable required to transmit the electrical signal. In the measurement settings, the device was set to measure the speed of the signal, which then transmitted a low-frequency wave of 22 kHz to measure the maximum value of the energy of these waves. In this way, the speed of the signal propagation is related to the dynamic modulus of elasticity (MoE), while the attenuation of the signal energy is related to the characteristics of the material with which it is directly correlated (grain direction, lumps in wood, degradation zones in wood, etc.) [12, 13].

(1) Probe position labels,
(2) Ultrasound indirect longitudinal test,
(3) Ultrasound radial test,
(4) Moisture content measurements,
(5) Rot inspection

Figure 10. Material properties determination – ND tests and used devices [1, 2]

2.3.2. RESULTS OF NDT SURVEY

Based on the conducted hygrometric tests on the equilibrium moisture content of wood, which varies between 12.4% and 13.8% for Hangar 1, between 12.0% and 14.8% for Hangar 2, and between 12.4% to 13.4 % for Hangar 3 (depending on the probe position, where three measurement were made for each probe) it can be concluded that the average measured values are 13.2% for Hangar 1 and Hangar 3, and 12.9% for Hangar 2. As the equilibrium moisture content in the wood does not exceed 20%, it may be considered that the existing structure meets the requirements for service class

2. In Table 1, average results of the indirect longitudinal ultrasonic measurement are presented for Hangar 1, obtained for four characteristic probe groups (each group contains three probes).

Table 1. Average measured values and obtained results for four characteristic groups

Hangar 1 Groups	Sylvatest-Trio / stress wave NDT				Sylvius software – results			
	L	t_i	v_i	Peak energy	v	$E_{dyn,0}$	MoR	Assigned strength class
	(mm)	(μs)	(μs/m)	(mV)	(μs/m)	(MPa)	(MPa)	
I-1	1450	278	2599	18	5216	12892	35	C27
	730	137	2658	27	5315	13391	37	C30
I-2	1440	259	2776	25	5560	14624	42	C35
I-3	1380	241	2857	78	5726	15461	45	C40
I-4	1430	249	2864	35	5743	15546	46	C40
Used symbols: L – measured length; t_i – time of flight; v_i – measured speed; v – calculated speed (considering influence of measured moisture content), $E_{dyn,0}$ – dynamic modulus of elasticity (MoE, parallel to grains), MoR – modulus of rupture Note: Sylvius is an in-field data acquisition software for Sylvatest-Trio measurements (see also Figure 10)								

For the indirect longitudinal stress wave test (using Time of Flight ND technique), the acquisition software provides data on the dynamic modulus of elasticity and the estimated bending strength on the basis of the data on the measured moisture content and peak energy as well as the botanical type of wood (larch) and assigns a strength class. The average measured values of the dynamic modulus of elasticity $E_{dyn,0}$ are: 14.70 GPa (Hangar 1), 14.63 GPa (Hangar 2) and 15.38 GPa (Hangar 3). The values of the static modulus of elasticity, $E_{0,mean}$ were preliminarily estimated as 10% of the reduced $E_{dyn,0}$ value and assigned to strength classes. The mean density values, ρ_{mean}, calculated from the dynamic modulus of elasticity and the squared values of the wave speeds (v) correspond to the assigned strength classes according to EN 338:2016 [14]. Table 2 lists the calculated values of the material properties for the hangars and the assigned strength classes.

Table 2. Mean values for material properties and assigned strength classes

Hangar 1			Hangar 2			Hangar 3		
$E_{0,mean}$	ρ_{mean}	Strength class	$E_{0,mean}$	ρ_{mean}	Strength class	$E_{0,mean}$	ρ_{mean}	Strength class
(GPa)	(kg/m^3)		(GPa)	(kg/m^3)		(GPa)	(kg/m^3)	
Average mean values								
13.23	472.4	C35	13.19	472.5	C35	13.83	470.1	C35
Corrected mean values (standardized to equilibrium moisture content, MC = 12%)								
13.17	472.5	C35	12.86	472.7	C30	13.69	470.5	C35

2.4. DISCUSSION ON CONDUCTED INITIAL ASSESMENT AND CONCLUSIONS

On the basis of the conducted preliminary investigation work and the obtained results, it is clear that further measures can only be taken in two directions: to carry out a detailed condition assessment of the structure with a proposal for restoration measures, or to remove and replace it with a facsimile of similar typology and geometry. From the point of view of today's safety and usage requirements, as well as the requirements for reuse, the existing structure has obvious deficiencies:

- Connections with a single fastener are not considered load-bearing, and the connection made with a single bolt (note that they are all corroded) can have a very negative impact on the load-bearing capacity and flexibility of the entire structure (especially in the case of replacing existing solid gables with softer structures).
- The thickness of the lamellae (50 mm) is potentially questionable from the point of view of fire resistance (any increase in the thickness of the lamellae necessarily changes the geometry of the mesh and the way the lamellae are connected together).

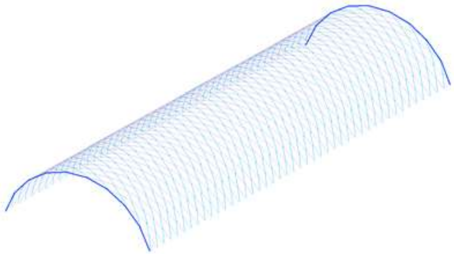
In the context of planning any renovation, a cost-benefit analysis (including the time) is certainly a key decision parameter, and a detailed assessment of the structure with the implementation of a static analysis with built-in geometric parameters and material properties must precede the proposal of any procedure. Although a detailed assessment of the structure was not planned at this stage (nor possible considering future architectural interventions related to repurposing), the attractiveness of the structure and the fact that it is still "standing" despite the identified defects, age and neglect, encouraged us to continue the research.

3. RESEARCH CONTINUATION AND PRELIMINARY RESULTS

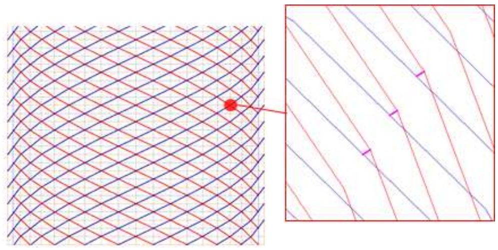
An additional reason is that over the last decade scientific and professional interest in grid timber structures has increased, as can be seen from the published works [15, 16, 17, 18]. The motivation for continuing this research also lies in the fact that the typology of the connection influences the geometry of the lamellae and the entire vault as well as the way it is executed. At the same time, the failure mechanisms of this type of connection have been studied little or not at all, although it is basically innovative and guarantees a simple and fast execution of the structure.

3.1. GEOMETRIC MODEL OF EXISTING STRUCTURE

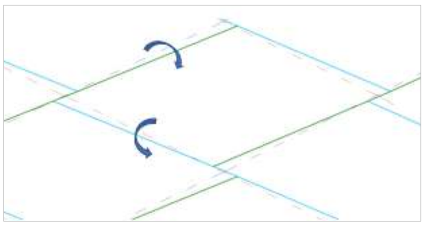
Although the shape of the vault exhibits a relatively simple geometric form, beneath it lies a diamond grid constituted by numerous straight elements with complex geometric relations. As the vault contains nine lamellas per arch, the curves are more flowing and the lamellas themselves look elegant and lithe. Structure geometry can also be considered as an assembly composed of two sets of oppositely oriented arches (Figure 11.1) that can be justified by insight into distribution of internal forces along the lamellae. Arches of each group appear iteratively at regular intervals along the longer side of the building ensuring global structural stability by mutually supporting each other. Furthermore, each arch consists of several individual elements (lamellae) whose axes do not coincide which is essential to enable a single bolt connection. Adjacent lamellae are connected at the intersection of two arches. The connection between the two lamellae does not occur at the same position as the connection between oppositely directed lamella elements; but passes through the centre of opposite lamella. An alternate position of connections is achieved by varying the length of the first lamellae in the group – one group of arches begins with a full-length lamella while the opposing arch starts with a half-length lamella. A favourable consequence of such a configuration is that the connection between lamellae, which could be regarded as a "weak point" of the structure, is supported by a relatively rigid point ensured by the lamellae from the opposite direction. Individual arch therefore follows a segment of the spatial curve – cylindrical helix (Figure 11.2), providing the uniform length of all internal lamellae. Furthermore, to enable an eccentric connection of the elements, each lamella is rotated around its vertical axis at its midpoint (Figure 11.3) [15]. Such spatial configuration also necessitates specially shaped element ends, which must be cut at specific angles to obtain compatible inclination. The exact geometry within the connection area has been extensively explored in the literature [19] as well as the curvature of the lamella upper edge which is necessary to obtain a final smooth surface of a barrel vault. Before recreating the existing structure geometry, a few key geometric parameters have to be accurately measured, as it is shown on Figures 6, 7 and 9. There is a strict mathematical correlation between such parameters and measurement inaccuracy that could lead to an incorrect model with variable lamella length or angles.

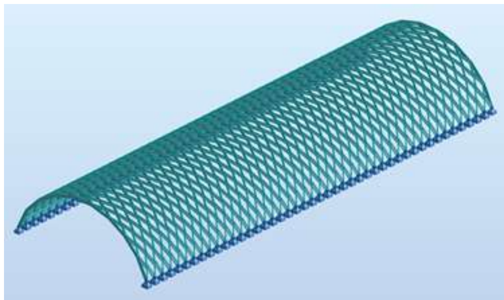


1. Reconstructed geometry of Hangars



2. Imaginary axes (lines that connect supports) around which real elements rotate)





3. ECCENTRIC CONNECTION AND LAMELLAE ROTATION (LEFT) 4. INITIAL GEOMETRIC MODEL (RIGHT)

Figure 11. Reconstructed geometry of Hangars and created initial geometric model

3.2. INITIAL EXPERIMENTAL RESEARCH ON JOINT STIFFNESS

Two sets of Zollinger connections, each containing 8 samples, were planned to be experimentally investigated at the Laboratory for Structures at the Faculty of Civil Engineering, University of Rijeka. Connections were constructed of spruce lumber and consisted of two 0.5 m long lamellae having cross-sectional dimensions 50/150 mm and one 1.0 m long lamella having cross-sectional dimensions 50/220 mm. Lamellae were connected with a threaded rod/M16 bolt and steel square washers. The first phase of testing was planned to be conducted on the set containing specimens made of brand-new timber, whereas the second phase was planned to be conducted on the set containing specimens made of old spruce planks previously used for another purpose (lumber without structurally unacceptable dimensional and other anomalies). The ends of the shorter lamellae were cut at an inclined angle of 45°, while the geometry and the position of the holes for the bolt correspond to the original configuration (Figure 4). It was planned to investigate four samples with covering boards and four samples without boards in every test group. Spruce boards with cross-sectional dimensions 24/150 mm and a length of 1.0 m were intended to be nailed to lamellae as such conditions represent the actual structure state. Visual investigation and ND tests were conducted on timber material to determine the mechanical properties (Figure 12). The density obtained from the measured dimensions and mass varies in the range 455.5 – 482.7 kg/m^3 for the new lumber and 449.9 – 475.3 kg/m^3 for the old one. Dynamic Modulus of Elasticity was defined within the range 14.8 – 16.45 GPa for the new lumber and 13.7 – 16.6 GPa for the old one. Finally, strength classes were assigned to the investigated lumber: C35 – C45 for the new one and C30 – C40 for the old one. It was concluded that strength classes, together with other material properties, correspond to the timber material of investigated Hangars.

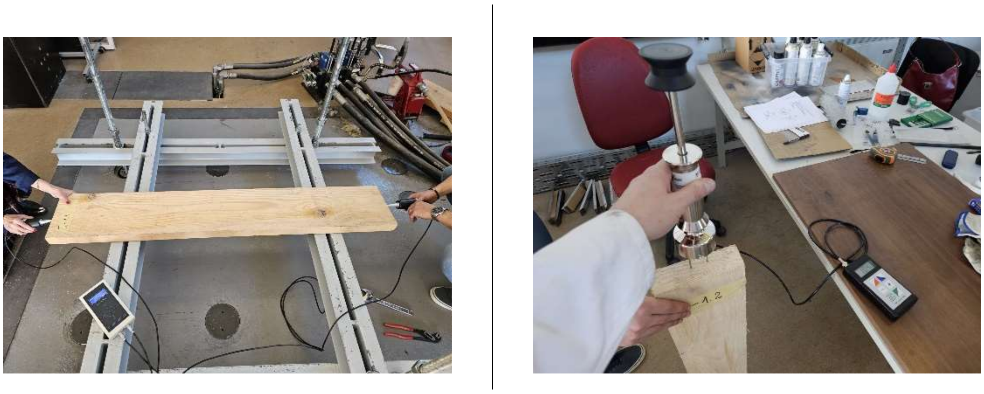


Figure 12. Material properties determination – planks used for manufacturing specimens

Although the comprehensive destructive laboratory tests of the Zollinger connection were planned, only a preliminary test conducted on two additional samples is shown in this paper. During the following detailed testing, displacements will be measured using LVDT at positions critical for understanding behaviour and determining the stiffness of the connection, while the displacement field will be also measured using digital photogrammetry. The purposes of the preliminary testing are defined as follows: to determine the suitability of the test setups, to reassess assumptions about force transfer among the lamellae and connection behaviour, and to examine failure mechanisms. The preliminary testing of additional samples was conducted within a steel frame with the frame sides composed of double-welded UNP profiles, whereas the frame elements were connected by bolts. Furthermore, the frame was secured to the reaction floor using threaded rods with a diameter of 32 mm. Force was applied via a cylinder press using a manual pump with a capacity of 100 kN (type RC 101), as it is shown on Figure 13. During the testing of preliminary samples, deformation of the steel frame was observed, which occurred due to an underestimated connection capacity. Therefore, in the continuation of the planned experimental research, it will be necessary to reconsider the test setup and equipment.

The failure force was assumed based on an experiment available in the literature, where the samples were scaled (1:2) [18]. The underestimated capacity suggests nonlinear and complex relationships between the dimensions of the components in the connection and the failure force. The connection failure occurred during a repeated attempt, and the failure pattern resembles the damage observed in the structure (Figure 8) – crushing around the hole combined with shear failure and a longitudinal cracking extending from the hole (Figure 14).

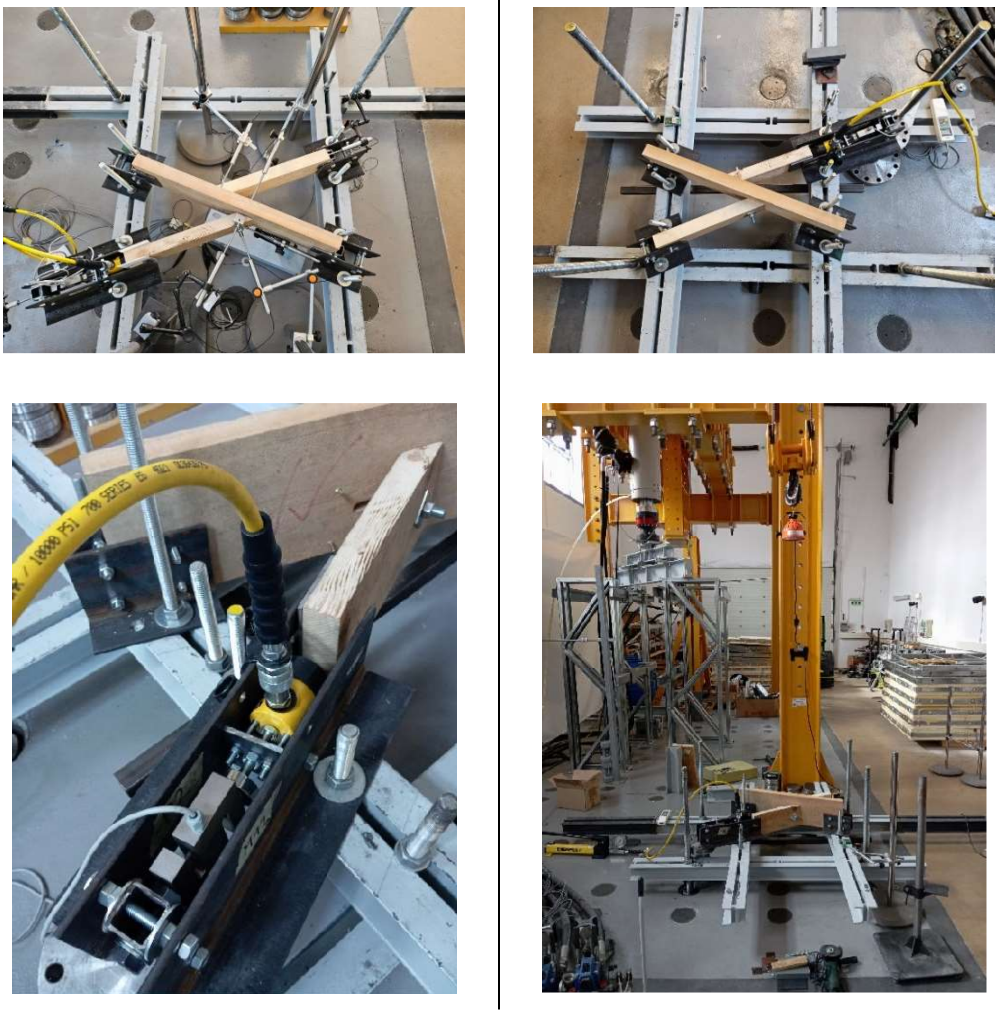


Figure 13. Setup of preliminary destructive test and equipment

Figure 14. Observed types of failures

4. FINAL DISCUSSION AND CONCLUSIONS

The global objective of sustainable development has been greatly directed toward the preservation of existing structures. Therefore, condition assessment and reconstruction of existing timber structures have been gaining importance in recent times. In this paper, some of the non-destructive and semi-destructive methods frequently used for timber structures are pointed out as promising methods for a quantitative description of the current condition of timber members and as a prerequisite for any further action and for conducting a detailed condition assessment of the structure. The results and conclusions derived from the preliminary condition assessment of wooden material of Hangars are presented and discussed in chapter 2.3, and guidelines for further research are given. They are focused on implementation of all key parameters - geometry of the structure and structural members and material properties, as well. Considering the uniqueness of the architecture and structural features of structures which were investigated in this case study, special attention was given to its geometry and joint typology. Prepared preliminary geometric model is presented and discussed, as well as the results of conducted experimental research on joint stiffness. The expected objectives of the experimental research, which is planned to be continued on a larger scale, are to provide better understanding of the failure mechanisms of the connection, to determine the stiffness properties of the connection and to incorporate them appropriately into the structural model, and to examine whether the covering planks (an integral part of the original vault typology) has an influence on the stiffness of the structure and how it can be simulated in the model.

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