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STATIC CALCULATION AND CONSTRUCTION OF GLUED LAMINATED ANTENNA TOWER

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ABSTRACT: Antenna towers with telecommunication equipment surround us and are often perceived as structures that disrupt the landscape. Glued laminated timber is a material with exceptional mechanical and visual properties, offering high durability due to well-designed structural details. This paper presents a load analysis, a numerical model with a static calculation, and the construction process of a 40-meter-high antenna tower with telecommunication equipment. The supporting structure of the antenna tower is made of glued laminated timber of strength class GL30c. Such structures can be acceptable even in protected areas where the construction of steel antenna towers is not permitted. One of the key advantages is the significantly lower carbon footprint of these towers, which will play an increasingly important role in the future.

KEYWORDS: Anntena tower, Glued laminated timber, Static calculation, Mechanical properties, Durability

1 – INTRODUCTION

Antenna towers are predominantly made of steel. However, due to significant fluctuations in steel prices on the market in 2020, alternative materials have been explored. Wood, as a construction material, is often perceived as less durable, with wooden structures considered temporary or having a relatively short lifespan. [1] On the contrary, glued laminated timber is characterized by exceptional mechanical and visual properties, high durability due to well-designed structural details, and low volumetric mass. Croatia generates significant revenue from tourism and is known for its natural beauty, with certain areas classified as national parks and nature parks. Considering these natural landscapes, some local government units prohibit the construction of steel antenna towers, as they would disrupt the scenic views of rural and picturesque areas. For these reasons, glued laminated timber is a logical choice as an alternative material. Locations in Croatia where such antenna towers have been built include Podcrkavlje, near Slavonski Brod; Gradići, near Zagreb; and Doljani, near Daruvar. These towers have a height of 40 meters, with a building ground plan of 5.16 meters × 4.46 meters.

2 – CONDITIONS FOR CONSTRUCTION

Based on spatial planning regulations and the guidelines of the Croatian Regulatory Agency, Croatia is divided into circular zones, with only one antenna tower permitted within each zone to prevent uncontrolled construction of such structures. Currently, three telecommunications operators operate in Croatia, and when designing the supporting structure of the tower, it must be dimensioned to accommodate the necessary equipment for all three operators. Croatia has a geographically diverse landscape, extending from the plains of Slavonia, across the Velebit and Dinara mountain ranges, to the Mediterranean regions of Istria, the coastline, and Dalmatia. This geographical diversity results in varying dominant loads when constructing structures. Regarding snow loads, [2] Croatia is classified into four zones according to *Eurocode 1: Actions on Structures – Part 1-3: General Actions – Snow Loads* and its *National Annex*. [3] The intensity of snow

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loads depends on the altitude of the structure's location. However, for this type of construction, snow is not a dominant load due to the small ground plan and tall structure; wind loads prove to be the most critical factor. According to *Eurocode 1: Actions on Structures – Part 1-4: General Actions – Wind Actions* and its *National Annex*, Croatia is divided into seven wind zones, where the basic wind speed $V_{b,0}$ ranges from 20 m/s to 48 m/s, depending on the geographical location. [5] [4] Additionally, terrain category significantly impacts wind intensity calculations. Category 0 applies to open sea or coastal areas exposed to the open sea, while Category 5 refers to areas where at least 15% of the surface is covered with buildings exceeding 15 meters in height. Considering terrain category, the exposure factor $c_{e(z)}$ can be significantly higher for structures in open, obstacle-free areas. In rural and uninhabited coastal areas—covering a substantial portion of Croatia—wind load calculations often reach extreme values. Croatia is also a seismically active region due to the subduction of the Adriatic microplate beneath the Dinarides, caused by the movement of the African plate relative to the Eurasian plate. [6] However, glued laminated timber antenna towers are highly elastic, with long natural vibration periods, meaning seismic forces do not represent a significant load, even in the case of moderate-intensity earthquakes.

3 – PROJECT DESCRIPTION

The construction of telecommunication antenna towers is frequently undertaken in rural areas, often on plots that are challenging to access due to the absence of adequately developed access roads capable of supporting heavy construction machinery. The designated construction site in Podcrkavlje, near Slavonski Brod, presented such challenges, being located on a moderately sloped terrain. Consequently, the initial requirement for the investor, Markoja d.o.o., was to develop an access road with sufficient compaction to facilitate the transport and operation of construction equipment. The structural design of the tower was based on glued laminated timber beams, which were further stabilized and connected using steel elements. The primary load-bearing system comprises wooden components forming a core with an equilateral triangular cross-section. Additional structural rigidity is achieved through three linear laminated beams of varying heights, positioned at 120-degree angles relative to one another. Within the core of the tower, steel plates are integrated and fastened with screwes to ensure a secure connection between the wooden elements. To optimize transport and assembly, the wooden structure was divided into four segments, each measuring 10 meters in length. The foundation of the tower consists of a base with dimensions of 700 cm × 700 cm × 220 cm, while the upper section accommodates four prefabricated steel platforms designed to facilitate the installation and maintenance of telecommunication equipment. The completed timber load-bearing structure is engineered to support antennas and all associated telecommunication infrastructure necessary for signal transmission to end users.

Figure 1. Photograph of the Podcrkavlje, Croatia location during the execution phase of preparatory works.

4 – LOAD ANALYSIS AND NUMERICAL MODEL WITH STATIC CALCULATION

The structural load analysis and load combinations were conducted in accordance with *Eurocode: Basis of Structural Design* [7], *Eurocode: Basis of Structural Design – National Annex* [8], *Eurocode 1: Actions on Structures – Part 1-1: General Actions – Densities, Self-weight, Imposed Loads for Buildings* [9], as well as the relevant standards governing snow and wind loads. The permanent loads acting on the structure include the antenna equipment and associated cabling, the specifications of which are provided by each telecommunications operator, four prefabricated steel platforms, and the weight of the steel connecting elements that integrate the laminated glued timber beams into a unified structural system.

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Figure 2. Display of steel assembly platforms for the installation of antenna equipment.

It is also important to note that the software package used for the numerical model independently calculates the self-weight of the wooden elements of the primary load-bearing structure by utilizing the volume of each element and the material's volumetric weight. The basic wind speed $v_{b,0}$ at the Podcrkavlje location, according to the reference map, is 20 m/s, while the selected terrain category is III.

Figure 3. Podcrkavlje, Croatia location on the map with a representation of basic wind speeds.

According to *Eurocode 1: Actions on Structures – Part 1-4: General Actions – Wind Actions* [4], terrain category III is defined as areas with a continuous cover of vegetation or buildings, or areas with isolated obstacles spaced no more than 20 obstacle heights apart (e.g., villages, suburbs, permanent forests), while terrain category II is defined as areas with low vegetation, such as grass, and isolated obstacles (trees, buildings) spaced at least 20 obstacle heights apart. The subject location can be classified according to the typology of both categories, considering that it is surrounded by a permanent forest. However, graphical supplements from the relevant standards did not provide precise guidance in defining the terrain category for this location. Following consultations with the project supervisor, the structural designer determined that terrain category III most accurately corresponds to the location, which was ultimately selected for calculating the exposure factor $c_{e(z)}$. In the tower zone at a height of 30 to 40 meters, antenna equipment is installed at three levels to ensure optimal coverage. Each antenna has a predefined spatial position according to the project and, depending on its placement, represents an additional exposed surface in terms of wind load effects. The load-bearing structure of the tower does not have the open framework characteristic of steel lattice towers, meaning that the entire structure acts as a barrier to wind forces. This characteristic defines the solidity ratio φ as 1.0 in calculations. For wind load analysis, the 40-meter-high tower was divided into 5-meter segments to account for the increase in wind speed with height, which consequently results in greater wind load intensity in the upper zones of the structure. *Eurocode 1: Actions on Structures – Part 1-4: General Actions – Wind Actions* [4] does not provide specific guidelines for calculating the force coefficient $c_{f,0}$ for a structure with an equilateral triangular cross-section. However, *Eurocode 1: Actions on Structures – Part 1-4: General Actions – Wind Actions – National Annex* [5] defines two values for $c_{f,0}$: 1.20 for wind flow impacting the apex of the triangle and 2.00 for wind flow impacting the sides of the triangle. The wind load analysis across all segments demonstrates a significant increase in wind force with height for both apex and side wind flows. In the 0–5 meter zone, wind intensity for apex flow is 0.24 kN/m², while in the 35–40 meter segment, it reaches 0.70 kN/m², representing a 2.9-fold increase. For side wind flow, intensity increases from 0.39 kN/m² in the 0–5 meter zone to 1.11 kN/m² in the 35–40 meter segment, a 2.85-fold increase. These values indicate that, for structures of this type, wind represents the most critical loading condition, with a particular emphasis on the effects of increasing height.

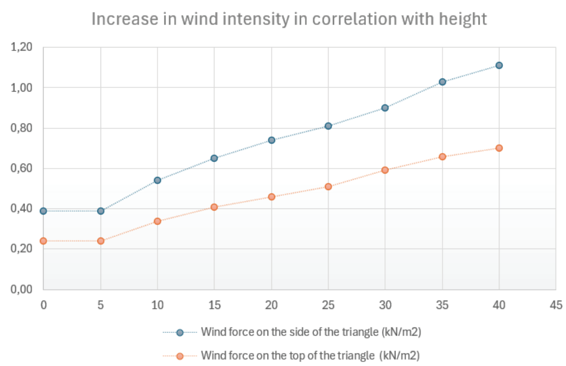

Table 1. Increase in wind intensity in correlation with height

The numerical 3D model was created using the *Tower 8* software package for static and dynamic analysis of structures. The structure was modeled using linear beam elements, which were applied to the wings of the structure, and plate elements, which were used for connecting the wings at the base of the tower. The numerical model included three linear supports and three point supports. All supports were released from the transfer of bending moments around all three axes of the elements.

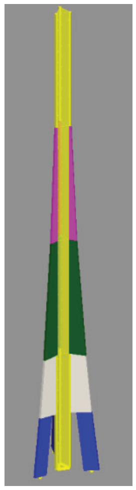

Figure 4. The numerical model of structure

The foundation structure was separately analyzed using the specialized geotechnical software package *GEO5*, in which bearing reactions were applied. The foundation slab was assessed in accordance with the ultimate limit state, considering soil failure, and the serviceability limit state, taking into account soil settlement. The foundation slab incorporated reinforcement mesh Q785 on all sides, distributed across three zones. In addition to the reinforcement, a supplementary steel structure, was installed to secure the timber tower. Geotechnical investigations provided the soil properties, which stipulated that prior to concreting, compaction (compressibility) of the substrate must achieve a minimum of 60 MPa, alongside the implementation of drainage beneath the foundation slab. The timber load-bearing structure of the antenna tower was designed to a height of 40 meters, which necessitated consideration of significant bending moments at the foundation level due to wind loads. Ensuring proper compaction beneath the foundation and preventing differential settlement are critical factors for the stability and functionality of structures of this type. Initially, the design of the timber load-bearing wings was based on homogeneous laminated timber of strength class GL24h, as per *Structural Timber – Strength Classes (EN 338:2016)* [10]. While Croatia is abundant in forest resources, it lags behind Western Europe in the production of high-strength laminated timber. Domestic manufacturing capabilities allow for the production of laminated timber in strength classes GL24h, GL24k, GL28h, and GL28k, which justified the initial selection of the GL24h class. Ultimately, the structure was fabricated in Finland by the company Ecotelligent, which was the originator of the tower design, and the chosen strength class was GL30c to ensure improved element density, enhanced durability and superior mechanical characteristics.

Figure 5. Glued laminated timber (GLT) wing elements of strength class GL30c.

All elements are designed with a maximum length of 10 meters to facilitate easier transport and assembly, especially in difficult-to-access terrain. In the joint areas, it is essential to ensure the transfer of longitudinal and transverse forces, as well as bending moments. The timber elements are connected to each other using bolts, steel plates, and additional steel structures within the core.

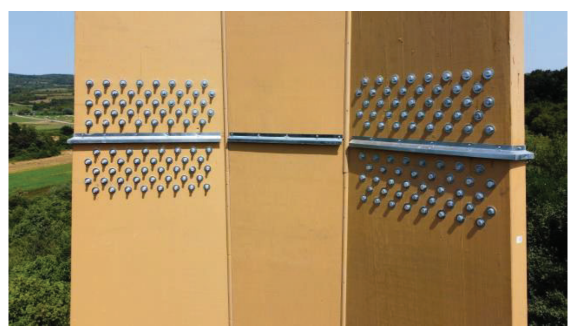

Figure 6. The extension of the pole that transmits the bending moment up to a height of 10 meters.

The wings at the foundation are interconnected using bolts and steel plates with, which provide structural stability under tensile and compressive loading conditions. The connection between segments 1-2, and segments 2-3 at a height of 10 meters and 20 meters, is designed with a recessed steel plate and bolts. The dimensioning of both the timber and steel components was carried out in accordance with the Ultimate Limit State and Serviceability Limit State for load combinations, in line with the relevant standards [7] and [8]. The expressions for the verification of the strength of the elements and cross-sections were derived from Eurocode 3: Design of Steel

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Structures – Part 1-1: General Rules and Rules for Buildings [11], Eurocode 3: Design of Steel Structures – Part 1-1: General Rules and Rules for Buildings – National Annex [12], Eurocode 5: Design of Timber Structures – Part 1-1: General – Common Rules and Rules for Buildings [13], and Eurocode 5: Design of Timber Structures – Part 1-1: General – Common Rules and Rules for Buildings – National Annex [14]. The location identified by the designers as critical, and with the highest utilization when proving the ultimate limit state, is the wing of the pole at a height of 2.5 meters, where acts a longitudinal compressive force interacts with a bending moment. In the calculation of the design strength of the materials, the usability class used is the third, due to the constant exposure of the structure to atmospheric conditions, and the moisture content in the timber at hygroscopic equilibrium will exceed 20% [15].

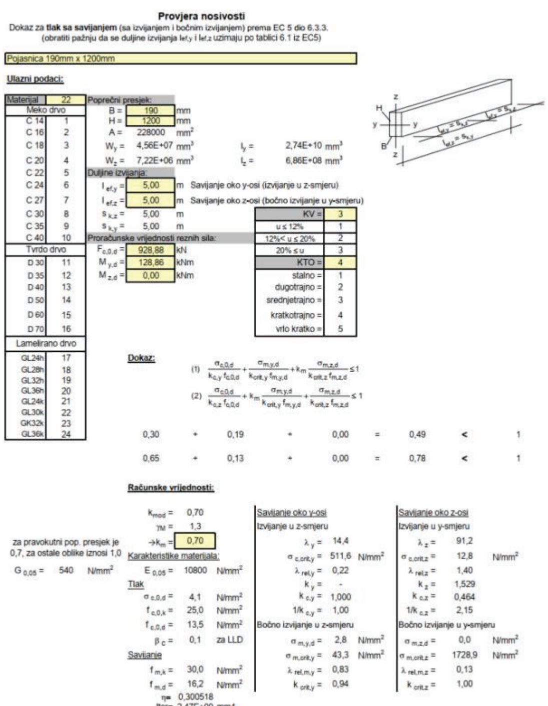

Figure 7. Dimensioning of the column wings at a height of 2.5 meters according to the ultimate limit state.

When dimensioning the elements, checks were made at critical positions by analyzing internal forces and bending moments in correlation with the changing cross-section of the column wings. During the calculation of the extensions that must withstand bending moments, the maximum bending moment that a bolt can take was calculated for each connection, depending on the bolt's position in the detail, and the maximum stress for the reference failure mode of the connection was defined. This way, stresses for each connection and the overall load-bearing capacity of the detail were determined. The serviceability limit state was checked for wind load combinations acting on the side of the triangle and on the top of the triangle, including the deformation coefficient kdef, with the condition to be satisfied for the displacement at the top of the column being l/75, where l is the height of the column [16].

Figure 8. The maximum displacement of the column according to the serviceability limit state is 369.56 mm.

5 – CONSTRUCTION OF THE TOWER

The construction of the 40-meter-high antenna tower began in May 2023 with site preparation. After excavation, soil replacement was carried out to a depth of 60 cm, followed by the installation of geotextile, drainage, and the backfilling with stone material, all compacted to ensure the required soil density as per the project specifications. After setting up the formwork and reinforcement, the reinforced concrete foundation was executed in two stages: first by pouring a 100 cm thick layer, followed by the remaining 120 cm. A steel spatial anchor was placed into the foundation, onto which the steel supports for the timber antenna tower were mounted.

Figure 9. Assembly of the base and wings of the first segment on the reinforced concrete foundation

The timber wing elements are connected to the steel support using bolts, with bolt holes drilled on-site to ensure the optimal vertical alignment of the tower. The wings of the remaining segments were pre-assembled in the factory, with holes drilled for the bolts and the installation of steel plates to connect the segments. These steel plates were used during assembly to lift the timber elements into their designed positions. Special attention was given to the design and construction of the joint details to ensure the durability of the timber elements due to exposure to weather conditions. At all positions where water could potentially enter the joints and cause moisture accumulation in the timber, such as at the segment joints (Figure 6), metal flashings were installed to ensure proper sealing at the joints.

6 – CONCLUSION

The primary load acting on the structure is wind, which increases significantly with height, and this type of construction presents certain constraints in relation to wind zones and terrain categories. The timber load-bearing structure of the antenna tower has been identified as an optimal solution for locations characterized by a basic wind speed of 20 m/s and 25 m/s. The use of laminated timber elements, with their low volumetric mass, facilitates faster and more efficient assembly, especially in areas with difficult access. In the design of such structures, considerable attention must be given to the detailing process to prevent water retention in certain areas, as this could lead to the deterioration of the load-bearing components. A notable advantage of this tower is its reduced carbon footprint, which is expected to play a significant role in the future transition toward sustainable construction practices. Furthermore, the application of such structures may be particularly suitable for protected areas where the construction of steel antenna towers is deemed unacceptable.

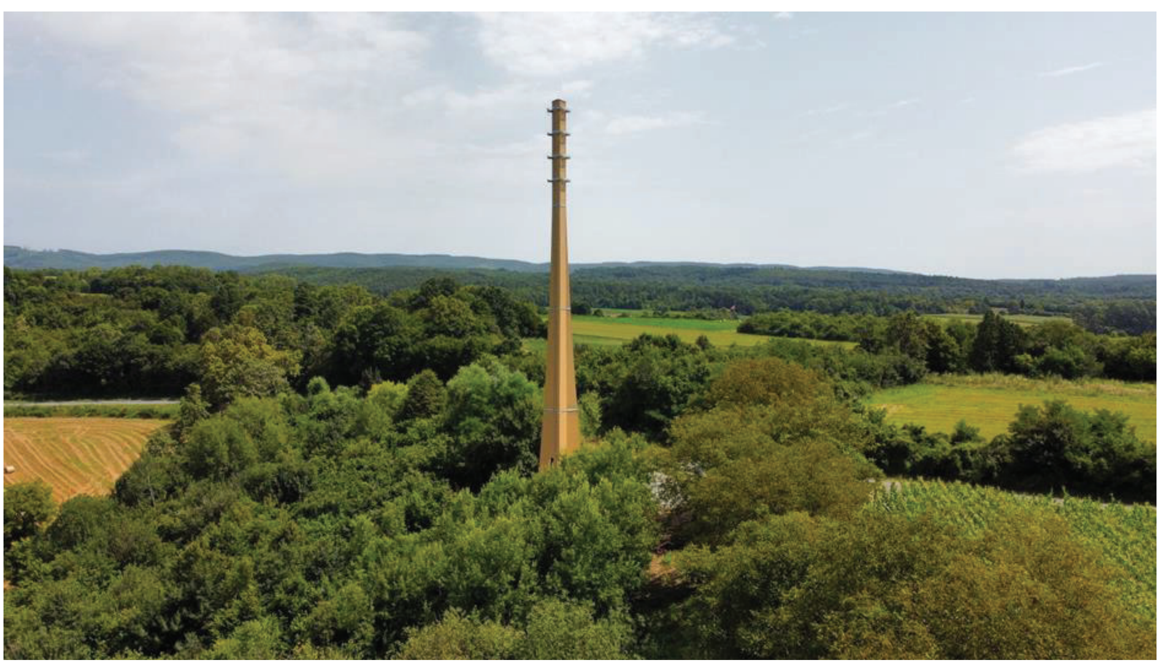

Figure 10. The antenna tower made of glued laminated timber was constructed at the Podcrkavlje location, Croatia.

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