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Glued Laminated Timber in Architecture

Lamelirano lijepljeno drvo u arhitekturi

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ABSTRACT • *Structural glued laminated timber (glulam) is an engineered, stress-rated product that consists of two or more layers of lumber (i.e., laminations) glued together with the grain running lengthwise. This article discusses typical shapes and sizes of glulam construction elements and static systems.*
This paper presents special stress conditions in the apex area of double-tapered beams with varying cross-section, curved and pitched-cambered beams. The results (tensile stresses perpendicular to the grain) obtained by the SAP2000 computer program are shown. In many cases these stresses are the crucial parameter that determines the size of the beam in the apex area.
The article discusses the most typical application of glulam elements and analyses its production and use in Slovenia and other EU member states. The study seeks to identify opportunities for increased use of glulam construction in Slovenia.

Key words: *wood structure, glued laminated timber (glulam), structural elements, composite*

SAŽETAK • *Lamelirano lijepljeno drvo moderni je kompozitni materijal koji se sastoji od tankih lamela uglavnom paralelnih vlakanaca. U radu se opisuje tipični oblik i veličina lameliranih lijepljenih nosača i statičkih sustava. Prikazane su posebnosti pri napregnutom stanju nosača od lijepljenog drva promjenjivog presjeka (osobito u sljemenoj zoni). Napravljena je analiza naprezanja računalnim programom SAP2000. Grafički su prikazana vlačna naprezanja okomito na vlakanca drva, koja su obično odlučujuća za određivanje dimenzija u sljemenoj zoni nosača. U članku se opisuje najčešća uporaba lameliranoga lijepljenog drva i analiziraju proizvodnja i uporaba u Sloveniji i drugim zemljama EU. Upozoreno je na mogućnost povećane upotrebe konstrukcija od lameliranoga lijepljenog drva u našem okruženju.*

Ključne riječi: *drvena konstrukcija, lamelirano lijepljeno drvo, konstrukcijski element, kompozit*

1 INTRODUCTION
1. UVOD

1.1 Glulam production
1.1. Proizvodnja lameliranoga lijepljenog drva

Glulam (also known as glued laminated timber, laminated wood, glulam beam, or classic glulam) is a composite material with more uniform distribution and higher values of mechanical characteristics than wood. Thin laminates are arranged so that the grain is generally parallel; they are glued together with structural adhesives that are rigid and durable, water resistant, and resistant to humidity, temperature, and biological factors.

Laminated construction elements are industrial construction elements characterized by a high degree of prefabrication. Glulam is one of the lightest construction materials. Moreover, due to its outstanding

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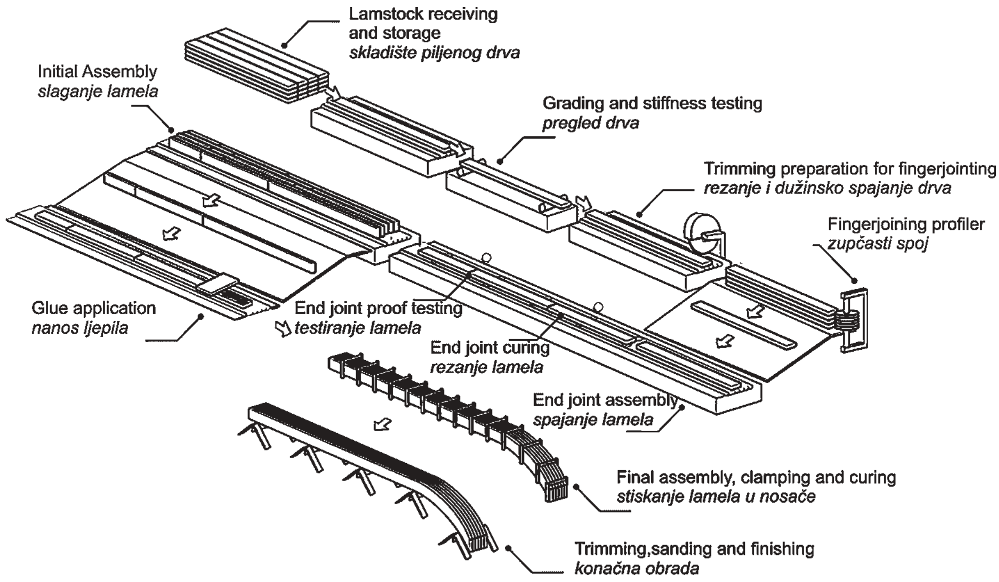

Figure 1 Manufacture of Glulam. Manuel de la construction en Bois (www.cwc.ca)
Slika 1. Shematski prikaz proizvodnje lameliranoga lijepljenog drva kontinuiranim postupkom. Manuel de la construction en Bois (www.cwc.ca).

elastic and mechanical characteristics it can be used for production of individual beams and columns as well as for large-span planar and spatial construction.

1.2 Laminates
1.2. Lamele

Although almost all types of wood can be used for glulam construction, the most common are top-grade spruce, fir, larch, and poplar. The wood has to be sound, suitably dry (maximum 18 (15±3) % moisture), and without great imperfections. Solid wood is first sawed into pieces and naturally dried, followed by kiln drying in order to achieve the desired degree of moisture content (Figure 1). Prior to use, the boards are stored in a temperature- and moisture-controlled warehouse. The moisture of the boards must be 1 to 2 % lower than the degree of moisture content upon later use. The difference in moisture content between individual laminates in one glulam element should not exceed 4 % (HRN EN 386).

Maximum thickness of laminates depends on the type of wood and service class. The maximum thickness for service class 1 and 2 conifer wood is 45 mm. The maximum thickness of laminates in curved elements depends on the curve radius and the characteristic bending strength of the wood. The net width of the laminates should not exceed 20 cm, and the gross width should be 21 cm or less. The width of the elements can be increased up to a maximum of 30 cm. With this width, two laminates form one row. Alongside transverse and horizontal lamination, edge-bonding is necessary as well.

In order to prevent bending, it is important to choose appropriate boards for producing the laminates because the correct positioning of laminates for adhesion can reduce unwanted tension on the gluing surface. Laminates must be properly oriented according to the growth rings – when two laminates are used, the gluing surface is the convex part of the growth rings.

Laminates must be joined lengthwise together in order to achieve the necessary length of beams. The most common is the wedged finger joint. The execution and minimum production standards are defined in the HRN EN 385 standard. The standard defines the finger joint as a self-centering tapered joint, shaped with machine milling of equal symmetrical tapering wedges, which are later glued together (Figure 2).

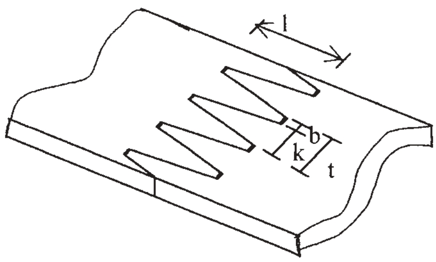

Figure 2 A finger joint (Müller, 2000)
Slika 2. Zupčasti spoj (Müller, 2000)

1.3 Adhesives
1.3. Ljepila

The development of synthetic adhesives has enabled versatile use of glulam construction. The requirements for structural adhesives are set forth in the HRN EN 301 standard. In some cases, using adhesives characterized by resistance to temperature, climate changes, chemicals, and microorganisms can give glulam construction an advantage over reinforced concrete and steel structures. The adhesive bonds wood into a new material. The adhesive must have mechanical characteristics such that the joint is practically non-deformable (Šernek *et al*, 1999).

Not all types of wood are suitable for gluing; the wood has to be porous enough in order for the adhesive to penetrate its cells. Improper adhesion can cause the joint to break. Fractures are often sudden (e.g., the collapse of the Ig Primary School gymnasium in 1980). The preparation of wood is an important factor for adhesion because it can entail significant changes in the wood characteristics. Wood drying can affect mechanical processing, wood stability, the interaction between the adhesive and wood during adhesive bonding, and the creation of internal stresses resulting from wood activity after adhesive bonding.

Phenolic and aminoplastic structural adhesives – urea formaldehyde (UF), melamine formaldehyde (MF), and melamine urea formaldehyde (MUF) adhesives – fall into two groups: Type I and Type II. This categorization takes into account the shear strength of joints, the resistance of the adhesive to delamination, cyclical strain of temperature and humidity, and strains caused due to wood shrinkage. The factors that influence the formation of the adhesive joint are application of the adhesive, application technique, assembly time, clamping pressure, curving time, temperature during bonding, and the conditioning of glulam. The color of the adhesive layer depends on the type of the adhesive.

2 CONSTRUCTION SYSTEMS AND STRESS IN TYPICAL ELEMENTS
2. KONSTRUKCIJSKI SUSTAVI I NAPREZANJA U TIPIČNIM ELEMENTIMA

2.1 Construction systems
2.1. Konstrukcijski sustavi

The use of glulam in modern construction depends on the successful cooperation of various specialists, especially the architect and building contractor. Usually, interior architecture depends on the choice of construction system. Today, there is a variety of different construction systems that enable top construction projects for different purposes. Load-bearing glulam systems can be categorized into the following groups: beams, three-hinged arches, frames, curved beams, consoles, and suspended structures (Figure 3).

Structures are categorized according to the predominant load (e.g., truss and axial load, beams and bending load) and the predominant load distribution (planar and spatial construction: cupolas, spatial frame constructions, spatial trusses, grids, and domes). Glulam systems allow practically unlimited choice in the dimensions of cross-section elements, they can cover extensive surfaces with large spans, and can easily adapt to modern architectural demands. The dimension of the load-bearing element depends on the static construction system, the load capacity of the material, production and installation technology, and the expected effect of the architectural composition of the construction.

2.2. Glulam beam and column cross-sections
2.2. Poprečni presjeci nosača i stupova od lijepljenog drva

Cross-sections are composed of laminates that are glued together. The choice among various types of cross-sections has increased with the development of increasingly stable and fire-resistant adhesives. This allows for various cross-sections (Figure 4). The most typical are the perpendicular, I-shaped, and composite box cross-sections.

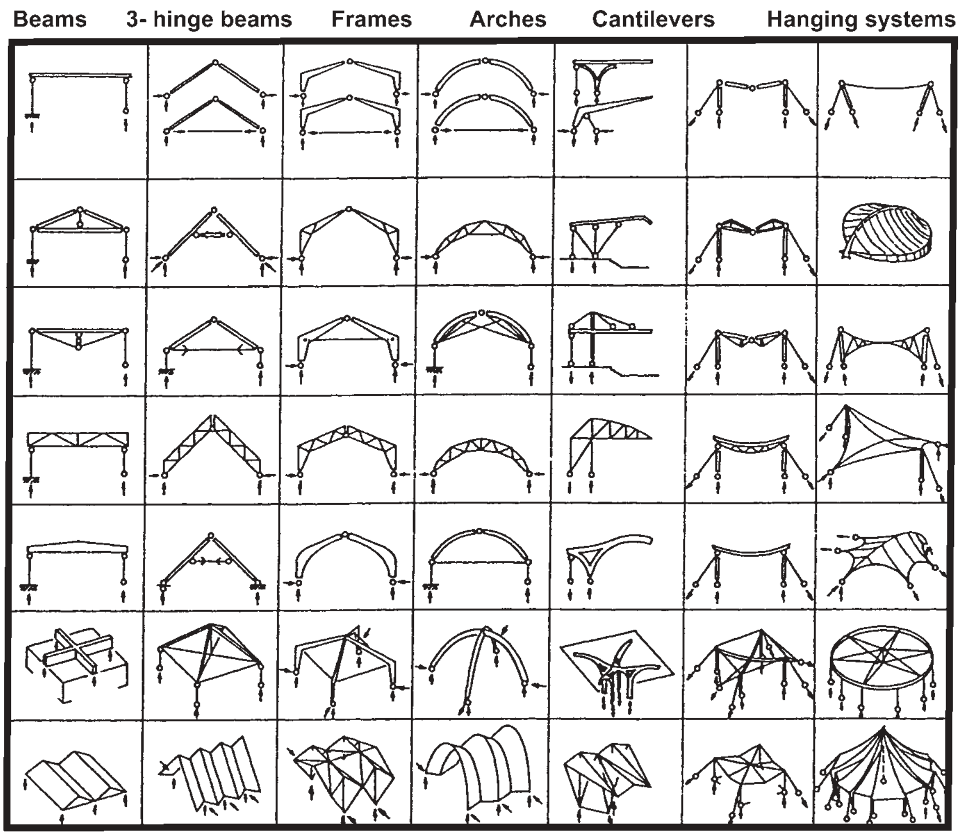

Figure 3 Wood structural systems: Beams – 3-hinge beams – Frames – Arches – Cantilevers – Hanging systems (Winter, 2004)
Slika 3. Grupe nosivih sustava: nosači – trozglobni nosači – okviri – zakrivljeni nosači – konzole – viseći sustavi (Winter, 2004)

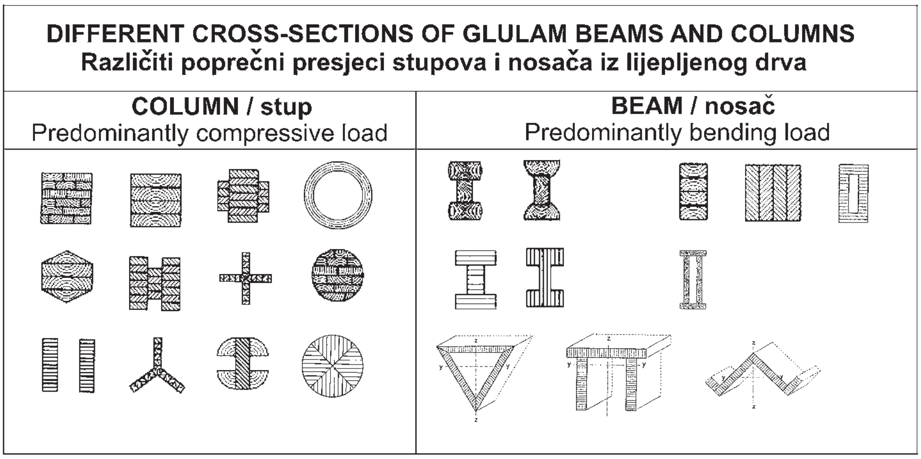

Figure 4 Glued members are available in a wide range of section sizes to suit every application
Slika 4. Različiti poprečni presjeci stupova i nosača od lijepljenog drva

The adaptation of the cross-section geometry to the direction of stress is based on this principle: as much material as possible must be positioned where it contributes most to the load capacity (i.e. to the edges, which bear the most stress).

2.3 Mechanical properties
2.3. Mehanička svojstva

The general requirements for glulam are defined in the HRN EN 14080 standard. Mechanical properties are established or experimentally defined with procedures prescribed in the HRN EN 408 standard.

Glulam strength classes are described in HRN EN 1194 (*Wood Constructions – Glued Laminated Timber – Strength Classes and Determination of Characteristic Values*). The standard categorizes and defines the use of two types of glulam: homogenous glulam (i.e., GL 24h, GL 28h, GL 32h, and GL 36h) and combined glulam (i.e., GL 24c, GL 28c, GL 32c, and GL 36c). The number following the label GL (glued laminated) is the characteristic bending strength in MPa (N/mm²). The inner part of the cross-section of combined wood is made from lower-strength wood. The minimum thickness of the outer part is one-sixth of the height of the element or two laminates.

The strength-class categorization can be based on test results of glulam patterns in line with the HRN EN 408 standard or following the calculation of glulam properties depending on the properties of laminated wood. Formulas for this calculation are cited in the HRN EN 1194 standard (Annex A).

2.4 Stress state in typical glulam beam shapes
2.4. Naprezanja u tipičnim oblicima nosača od lameliranoga lijepljenog drva

Successful introduction and widespread use of glulam requires standardization of the production process, quality control, production technique/technology, computer-analysis processes, and construction safety documentation. Extensive work is being conducted in the European Union in order to harmonize the European standards for structural load-bearing design from various materials (known as the Eurocodes). The regulations for wood construction (HRN EN 1995-1-1, 2005; Bjelanović and Rajčić, 2005) include procedures for designing or dimensioning various glulam beams. In addition to straight beams with a constant height, they address three other typical beam shapes (Figure 5):

- Single- or double-tapered straight beams (a),
- Curved beams (b) and,
- Pitched cambered beams (c).

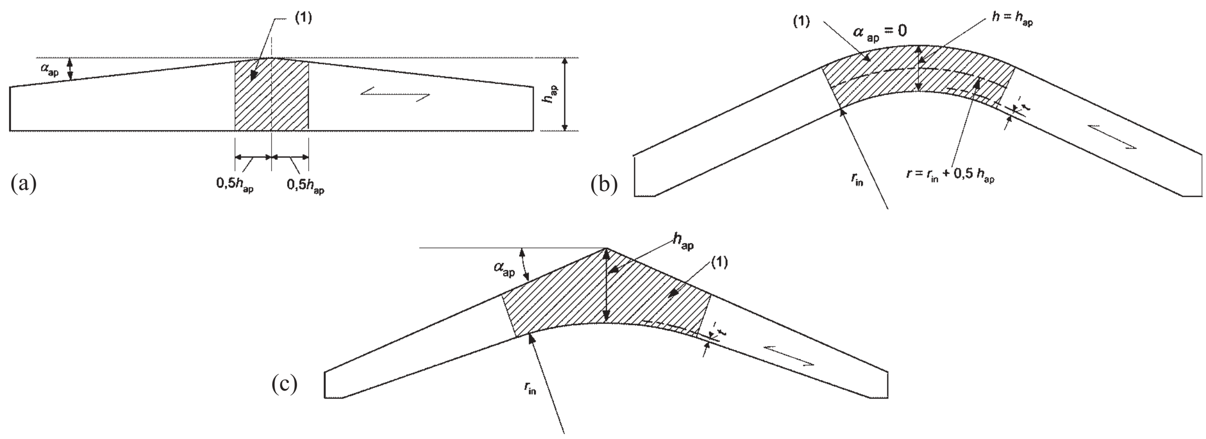

Figure 5 Typical glued laminated beams: (a) double-tapered beam, (b) curved beam and (c) pitched cambered beam; (1) apex area (HRN EN 1995-1-1, 2005)
Slika 5. Tipični oblici lameliranih lijepljenih nosača: (a) dvostrešni trapezni nosač, (b) zakrivljeni nosač, (c) sedlasti nosač; (1) – sljemena zona (HRN EN 1995-1-1, 2005)

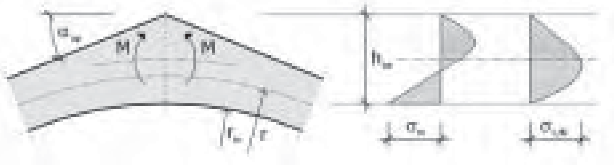

Figure 6 Special stress conditions in the apex area of a pitched-cambered beam. (σ_m – bending stresses, $\sigma_{t,90}$ – radial stresses; tension perpendicular to grain direction)
Slika 6. Naprezanja zbog savijanja σ_m i vlačna naprezanja okomito na vlakna drveta $\sigma_{t,90}$ u sljemenu sedlastog nosača

Shapes a and c have a variable cross-section height; curved beams can have a constant or variable height. Glulam technology enables the production of elements of different heights and shapes. By varying the height of the beams, it is possible to follow the flow of bending moments, which allows for greater use of cross-sections according to normal bending stresses. With the correct choice of construction shape and geometry, increasingly larger spans can be achieved. Glulam constructions have surpassed 100 m in span (Iimura *et al*, 2006).

The calculation of stresses for elements made of glued laminated timber is usually more complicated than for the elements made of other materials (Natterer *et al*, 1996; Žagar, 2002). The main reason is the variable geometry of the cross sections, inclinations of element edge regarding the grain direction in laminations and the curvature of element axis. For double-tapered beams with varying cross-section, curved and pitched-cambered beams, we should account for special stress conditions in the apex area (Figure 6). In addition to normal bending stresses σ_m, we should also expect tensile stresses perpendicular to the grain $\sigma_{t,90}$. These stresses are in many cases the crucial parameters that determine the size of the beam in the apex area, because the design tensile strength perpendicular to the grain is much lower than along the grain.

There is another solution for the beams with high tensile stresses perpendicular to the grain: special reinforcing devices can be used, which prevents the splitting of lamellas in radial directions. These can be made of wood, metal or even of carbon fiber reinforcement (Haiman and Rak, 2003; Johnsson et al, 2007). Wooden reinforcing devices are usually made of harder wood plates, which can be glued on both sides of the beam. The metal devices are usually internal steel screws for wood or threaded glued-in rods. Epoxy or PU resin should be poured in pre-drilled holes before mounting the transversal screws.

Different researchers, especially Möhler & Blumer (1978), have performed elaborate analyses of such beams and studied the effects of the afore-mentioned parameters on beam stress conditions. They have also proposed some expressions which enable the simplified analytical calculation of such beams, which were later included in many national codes and standards (also in HRN EN 1995-1-1, Chapter 4.2). With the rapid development of information technology, it is possible to analyze in more detail the stress state of such elements with suitable software based on the finite elements method (e.g., Sofistik, SAP2000, Tower, etc.). Glulam elements can be modeled as orthotropic walls with the correct direction of wood characteristics in given edge conditions. The software can take into account the different type of wood used in beams (with bottom and top parts made of better-quality wood). A comprehensive bibliographical review of the finite element methods (FEMs) applied in the analysis of wood products and structures can be for example found in the recent paper by Mackerle (2005).

A case in point is the stress state in the apex area of the pitched cambered beam. Alongside normal bending stress σ_m there are also tensile stresses perpendicular to the grain $\sigma_{t,90}$ (Figure 7).

Design and production should consider various construction demands in the HRN EN 386 standard regarding cross-section dimensions and individual laminates.

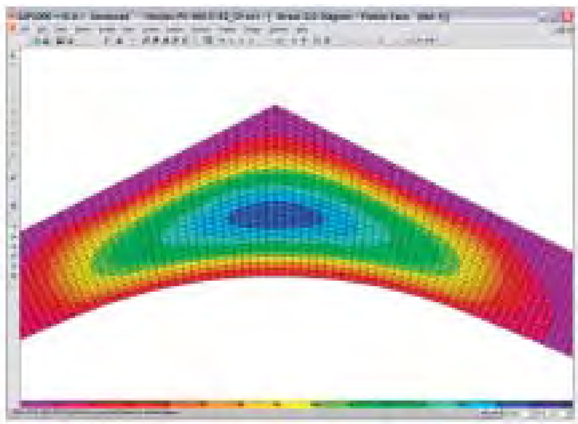

Figure 7 Part of the pitched-cambered (saddled) beam – tensional radial stresses in the apex area. (Analysis with computer program SAP2000; timber GL28h [E_1 = 1260 kN/cm^2, E_2 = 42 kN/cm^2, G = 78 kN/cm^2]; L = 16 m, b/h_{ap} = 20/171 cm, q_d = 21 kN/m; α_{ap} = 26.5°, r_{in} = 5.13 m; max. stresses $\sigma_{t,90}$ = 0.097 kN/cm^2.)
Slika 7. Dio sedlastog nosača – vlačna naprezanja okomito na drvna vlakanca (izračun u programu SAP2000; drvo GL28h [E_1 = 1260 kN/cm^2, E_2 = 42 kN/cm^2, G = 78 kN/cm^2]; L = 16 m, b/h_{ap} = 20/171 cm, q_d = 21 kN/m; α_{ap} = 26,5°, r_{in} = 5,13 m; najveće naprezanje $\sigma_{t,90}$ = 0,097 kN/cm^2.)

3 STRENGTHS AND WEAKNESSES OF GLULAM CONSTRUCTION ELEMENTS
3. PREDNOSTI I NEDOSTACI KONSTRUKCIJSKIH ELEMENATA OD LAMELIRANOG DRVA

3.1 Architecture and construction aspects
3.1. Arhitekturno i konstrukcijsko gledište

With regard to architecture, the main advantage of glulam elements is their versatility in form, which makes possible various shapes and dimensions (Figure 8). They have an aesthetic appeal and preserve elegance even with large spans.

As regards construction, one of the main advantages of wood constructions is their high loading capacity in relation to their own weight (e.g., 20% of the

Figure 8 Timber glulam construction (Hoja d.d., Škofljica, Slovenia)
Slika 8. Drvene lamelirane lijepljene konstrukcije (Hoja d.d., Škofljica, Slovenija)

weight of reinforced concrete). Glulam has several advantages over solid wood: better strength and rigidity, dimensional stability, various cross-sections possibilities, and the possibility of shaping the longitudinal axis of the beam. The comparison of waste produced between solid wood and glulam shows that the quantity of waste depends on the construction; the wider the beam, the better the utilization. The approximate estimate of utilization is ca. 1.5 m^3 of wood mass for 1 m^3 net of glulam beam.

3.2 Ecology
3.2. Ekološko gledište

Although aesthetic and economic considerations are usually the major factors influencing material selection, the environmental advantages of using wood may have an increasingly important effect on material selection. From the environmental viewpoint, wood biodegradability and the possibility of recycling are important factors. The production of glulam elements requires approximately twice the energy (1,218 KWh/m^3) as a comparable solid wood construction element (688 KWh/m^3) (Frühwald, 2005).

Adhesives are essential for the load-bearing durability of glulam elements. Many adhesives contain formaldehyde, which is harmful for health and is a burden on the environment. However, adhesive accounts for only approximately 1 % (Burgbacher, 1991) of the entire volume of the construction. As a result, the ecological advantages of glulam constructions are not significantly lower than those of solid wood constructions, especially when considering the almost inevitable use of metal connectors.

3.3 Fire resistance
3.3. Otpornost prema požaru

Glulam elements have significantly better fire resistance than is generally attributed to them, surpassing the fire resistance of steel and reinforced concrete beam structure. The capacity of wood to conduct heat is insignificant because it conducts heat 300 to 400 times more slowly than steel. The elements char slowly from the surface towards the inner parts. Charring reduces heat conduction and prevents oxygen from reaching the wood. In the non-charred cross-section the beams preserve full load capacity. In a normal fire, solid spruce wood burns at a speed of 0.6 to 1.1 mm/min and glulam at 0.1 mm/min. Glulam elements do not change shape during combustion. As a result, the beams do not exert pressure on peripheral walls and do not cause them to collapse.

Fire resistance of wood construction can be achieved if (1) the product is suitably dimensioned (HRN EN 1995-1-2, 2005), (2) it can be covered with fire insulation, or (3) it can be protected with chemical products, bearing in mind the actual purpose of the protection and choosing a suitable preparation.

4 USE OF GLUED LUMBER CONSTRUCTIONS IN ARCHITECTURE
4. UPORABA LAMELIRANIH DRVENIH KONSTRUKCIJA U ARHITEKTURI

Glulam is indispensable with constructions that require great strength, dimensional stability, and suitable aesthetic quality of the wood product (Stungo, 2001). In the EU, the largest share of glulam is used for non-residential buildings (commercial, sports and leisure, industrial, and cultural structures) (Figure 9). The share of residential buildings is 11 %.

There are various glulam elements with the possibility of combining different materials. These combined products include composite wood and polystyrene I-joists. Glulam elements can also have improved properties (curve, shear) due to pre-bending. There are also glulam beams with cross-sections that have laminates installed vertically in the stress zone or vertical laminates along the entire cross-section, glulam beams fitted with bands (steel, carbon laminates, or fiberglass

Figure 9 Modern timber construction Expo Roof - Hannover exhibition grounds
Slika 9. Suvremena drvena konstrukcija (Expo 2000, Hannover)

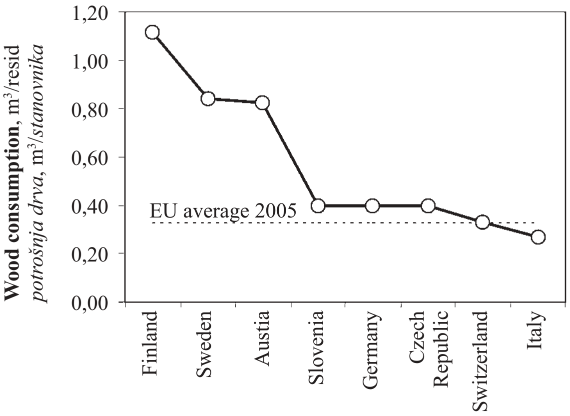

Figure 10 Wood products per capita consumption in selected EU countries, 2005 (Source: UNECE - analysed by M. Piskur, Slovenian Forestry Institute)
Slika 10. Potrošnja proizvoda od drva po stanovniku u nekim zemljama EU, 2005. (izvor: UNECE – analiza: M. Piskur, Slovenski šumarski institut)

laminates) (Natterer *et al*, 1996), reinforced pre-stressed beams, beams with epoxied threaded steel rods (Möhler and Hemmer, 1981), pre-stressed beams with external plastic cables, or elements reinforced with carbon-fibers, known as Carboglulam®, wood joints and laminated wood beams assembled by mechanically-welded wood dowels (Bocquet *et al*, 2007). Lately, there has been an increase in the use of wood and concrete composite constructions, especially in ceiling constructions.

Slovenian wood consumption is, according to official input raw data, relatively low compared to available wood resources, but nevertheless higher than the European average. Analysis done by SFI indicates that the actual consumption may be in the range 0.60-0.70 m^3/capita (Figure 10).

The use of wood in Slovenia in construction and engineering primarily focuses on wood in its natural shape and pays too little attention to designed products with higher added value. The sale of round timber is becoming increasingly difficult due to ever smaller capacities in primary wood processing (sawmilling and production of particle boards and panels) and chemical wood processing (cellulose production). High processing costs, a consequence of significantly smaller processing capacities in comparison with those abroad, and increasingly poorer quality of processed wood have caused Slovenia to lose its competitive edge in the glulam market.

According to CEI-Bois the production of glulam beams would be more than triple in the period between 1990 and 2010, primarily due to heavy exports to the Japanese market. It is expected that better use of existing and new capacities will also create growth in glued-wood production in Eastern Europe. Lately, Europe has been seeing a significant increase in the use of glued wood. It is expected that Asian countries, including Russia, will increase their supply. In Europe, the Mediterranean countries are prime importers; this trend is expected to continue in the coming years.

Slovenia significantly lags behind geographically comparable Austria in the production and use of glued wood; both countries have a similar share of forests. There are several reasons for this, but the primary ones are uncompetitive production and insignificant demand for glued wood. The annual use of wood and wood composites in various areas of construction is about 400,000 m^3; some 800,000 m^3 is used for furniture. The leading Slovenian manufacturer of glulam wood is the Hoja company, producing 3,750 m^3 net of straight and curved beams per year. The Svea and Legoles companies also produce glued wood. The Legoles production program includes cross-laminated timber (referred to as *KLH* '*Kreuzlagenholz*') as 50 % of production, two-layer (*DUO*) and three-layer (*TRIO*) glued construction timber as 20 %, glued laminated timber (*BSH* '*Brettschichtholz*') as 30 %, ceiling elements, and glued timber, adding up to 2,950 m^3 net per year. The Svea company has an annual production of 4,000 m^3 net.

According to some estimates, glued wood accounts for more than 50 % of the processed wood in Slovenia. In addition to glulam elements, glued wood includes wood-based panels (i.e., particle boards, oriented strand boards, fiberboards, and composite panels) and composite wood for construction: laminated veneer lumber (LVL), parallel strand lumber (PSL), and laminated strand lumber (LSL).

5 CONCLUSION
5. ZAKLJUČAK

Ecological concerns give glued wood a competitive edge over other materials; moreover, its outstanding physical, mechanical, and technological properties make it indispensable in construction. Its aesthetic value is highly appreciated because it enables the formation of demanding architectural shapes, the realization of new spatial concepts, and various construction shapes.

Optimization, milling, and gluing can improve glulam elements and make use of weaker wood, and even recycled wood. The production and use of laminated wood elements has increased all over the world. With new technologies that will enable improved accuracy in production and design, their use will only increase further in the future. The current state of production and low use of glulam elements in Slovenia is cause for concern. Nonetheless, promoting and raising awareness about the advantages of such construction can contribute to promoting laminated wood constructions.

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