REINFORCED GLULAM: AN INNOVATIVE BUILDING TECHNOLOGY

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Abstract

Wood represents one of the few renewable natural resources: coniferous timber is reproduced in nature with a quite short cycle allowing wide cultivation.
Glulam is an evolved technology: an industrial product that overcomes the defects of wood through technological production.

In the last decade, glulam has become a valid alternative to the more usual and traditional technologies of reinforced concrete and steel in the planning and in the realization of engineering works.

Since this technology has been widely available, one of the problems that needs to be overcome is the limited rigidity of the elements.
Up to now, glulam stiffening techniques have only been developed successfully in very simple static schemes that don't generally allow the full potential of the material to be exploited.

The paper will show the results of a study that has been conducted on the different technologies of glulam reinforcement for the purpose of obtaining an innovative product.
In conclusion, in this phase, the aim is to verify which of these innovative experiments can constitute a point of departure for a competitive technology to be produced industrially.

Keywords: reinforced glulam, sustainability, stiffness, FRP, composite, wood

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Introduction

The research carried out in the building industry in the last decade has been more and more orientated towards materials that are environmentally friendly and sustainable, in order to waste as few natural resources as possible. As a result, wood and in particular glulam, has become a valid alternative to the more usual and traditional technologies of reinforced concrete and steel, partly because it represents one of the few renewable raw materials.

Glulam, in particular, is an advanced product, an industrial product that overcomes the typical defects of block wood and has superior mechanical strength and durability, allowing it to take any shape and to reach a considerable size, thanks to the combination and gluing of the individual strips.
In recent years research has been driven towards experimentation to improve the structures in glulam, giving it more rigidity. Although research in this field has been active for many years, the "state of the art" is still in a continuous state of evolution.

This process has been slowed down, to a certain extent, by the lack of a specific set of regulations. Until recently there were no regulations to calculate and check structural factors, and there are still gaps in the regulations, especially with regard to reinforcement using composite materials.

A Brief Description of Usual Glulam

Wood is an anisotropic[1] material that behaves in an almost fragile and hygroscopic way. It has defects and altercations (knots, ring shakes, deviations in its fibre, fissures, …) and its mechanical characteristics are connected to the natural origin of the material and hence the species of the wood[2]. Even within the same species the characteristics vary depending on various parameters such as the type of forestry, the climatic conditions, the type of terrain, etc…. and they can also vary within the same plant: from the bottom to the top and from the centre to the outside, and based on the seasoning that it has undergone.

Wood has a very low specific weight. Infact its mass to volume ratio varies from species to species in a range between 0.15÷1 g/cm^3, but guarantees high levels of mechanical strength as a result of the morphology of the cellulose and the chemical structure of the walls.

The construction system of glulam has been applied on a vast scale from the 1970s onwards, and represents a natural renewable resource because the broad-leaf or coniferous timber that it is made with reproduces itself naturally with a fairly short cycle and is therefore an almost limitless raw material. What is more, glulam technology allows the trunk to be used in the most efficient possible way, reducing waste and making use of less valuable trees. The most commonly used wood in Europe is red deal, very widely grown, readily available and low cost.

Glulam is produced by the simultaneous application of two techniques: gluing and lamination. Lamination allows the inconsistency of the raw material to be overcome, discarding the defective parts; gluing, on the other hand, creates a mechanical connection between the fibres of the adjacent planks.

Production is developed through: the choice of the most suitable material, the preparation of the layers, the finger joints, the gluing and the finishing of the pieces.

The mechanical characteristics of glulam components are fundamentally influenced by humidity and therefore by the environmental conditions in which they are placed, and by the duration of application of the load (the regulations take this into account by introducing coefficients that limit strength values).

The timber used to make glulam beams is worked at a humidity of 12% corresponding to a condition of hygroscopic equilibrium of 20°C temperature and 65% relative humidity.

Three basic glues are used: Resorcinol-Formaldehyde, Urea-Formaldehyde and Melamine-Urea-Formaldehyde. These structural adhesives[3] have the capacity to transmit the actions in the connections to the strips by means of predominantly tangential tensions on the gluing surface, in such a way as to reduce the concentrations of normal stresses and tensions. They have high mechanical performance and good reliability over time. In fact, in comparison with traditional glues, they do not deteriorate as a result of biotic factors and atmospheric conditions.

EN 386 means that the gluing has to take place within 24 hours after the planing of the layers in order to avoid problems with taking, and that the pressing process has to be carried out with a pressure specified in the instructions provided by the manufacturer of the glue[4].

With the pressing, which takes place in special pressing beds, it is possible to improve the connection characteristics between the strips, but above all it is possible to curve the material, which means that a wide range of different shapes can be created.

There are no regulations that limit the dimensions of glulam. The only limitations are caused by the clamping and finishing equipment and by transport problems[5].

As far as the production is concerned, a detailed selection and arrangement of the strips can be made in the test piece. In fact, the strips with better mechanical characteristics are often positioned at the upper and lower ends and in the concavities of the rings near the bottom, except the last strip. This precaution is taken in order to reduce the risk of water getting in, and also because of possible aesthetic and structural drawbacks caused by the shrinkage of the material.

Wood is also sensitive to the effects of sunlight, which, together with humidity, temperature, wind and rain, give rise to the complex phenomenon known as aging because of photolysis. Although it is generally very resistant to chemical attacks, it is very sensitive to alkali and iron compounds that destroy the lignin and the hemicellulose causing the hydrolytic decay of the wood The superficial decay that all kinds of wood are subject to is mainly attributable to exposure to large amounts of sunlight (UV).

The effect of atmospheric agents on glulam can be described in a simplified way as the cyclic and irregular action of drying and humidification of the material[6].

Among the advantages of glulam are the fact that it is economic and the fact that it is a good sound and heat insulator. Among the disadvantages is the fact that it has limited stiffness. This has led to a huge field of research based on the possibility of adding stiffening components to the inside of the resistant section.

Innovative Strengthening Systems

Various different techniques have been developed to give glulam greater strength and stiffness. These include:

- fibres:
    - glass fibre (GFRP)
    - carbon fibre (CFRP)
    - aramide fibre (AFRP)
    - hybrid fibres (GFRP+AFRP, CFRP+AFRP, …)
- Steel bars
- Harder wood
- Harder wood and fibres.

STRENGTHENING WITH FIBRES

Most of the experimentation has been carried out with the use of fibres. We shall pay particular attention to these methods because the information acquired allows us to make an important comparison between the different trials.

In particular, the strengthening techniques with fibres are carried out with strips made with fibres and a mould.

Glass fibre shows a normal coefficient of elasticity equivalent to about 70÷90, tension strength of 1.1 GPa, a density equivalent to 2.55 g/cm³ and a heat deflection temperature of 110ºC. It offers a good ratio between product cost and performance requirements and an excellent compatibility with resins; it is also a material that is sensitive to creep.

Carbon fibre shows a normal coefficient of elasticity of 180 ÷ 700 GPa, a tension strength of 2.2 GPa, a density equivalent to 1.75 g/cm³ and a heat deflection temperature of 103ºC. It offers a high level of resistance to bending, tensile stress, compression and fatigue; however it is easily breakable, high cost and it conducts electricity. In relation to their weight, materials made of carbon fibre are superior to others.

Aramide fibre is an organic fibre made from orientated aromatic polymers. It shows a normal coefficient of elasticity of 70 ÷ 130 GPa, a tension strength of 2.8 Gpa, a density equivalent to 1.25g/cm³ and a heat deflection temperature of 109 ºC. It offers an extremely high resistance to shock and impact, as well as shearing stress and it has a great capacity to absorb kinetic energy and vibrations. In addition to all of this, it should be added that it has an excellent resistance to fire, heat and chemical agents, and good heat insulation and electrical insulation properties. However, it is difficult to permeate and expensive.

Hybrid fibres are obtained by mixing different fibres with a consequent optimization of the property/weight ratio and a reduction of costs.

The **polymeric matrix** has the function of holding all the fibres together and giving them resistance to breaking and to compression. In fact, when the matrix is subjected to stress, it can absorb energy by buckling. The matrix is usually an epoxy resin that is not very susceptible to the creep of the fibres and that does not absorb water and can be used at high temperatures, up to 160 ºC in some cases.

Good alternatives to this are phenolic, polyester, melamine, polyvinyl-acetate and vinyl-ester resins. The fibres can be either unidirectional or crossed. The most commonly used in these applications are the unidirectional ones, in parallel along the longitudinal axis of the beam.

Table 1. Allowable tensions of the strips in FRP set out in parallel along the longitudinal axis of the beam.

TYPE OF FRP REINFORCEMENT PANEL	GFRP	CFRP	AFRP	GFRP+AFRP	CFRP+AFRP
ALLOWABLE TENSILE STRENGTH (MPa)	241	834	986	241	834

The strengthening lame can be created through a process of pultrusione[7] or wet preg[8] (soaked and impregnated fibres), with a variable thickness of between 1÷10 mm, the strengthening lame most employed have a thickness of 2÷3 mm where better results are also obtained with regard to the cost/benefit ratio can be seen.

The lame has a volume ratio that varies from 58 ÷ 70% fibres and 30 ÷ 42% matrix.
The **adhesives** used for gluing between **FRP-wood** have an important role in transferring stresses between two materials that have different stiffness characteristics, chemical composition, compatibility with resins and thermal-hygrometric and mechanical behaviour. They are essentially epoxy, resorcin or phenolic based.

When constructing a reinforced beam it is necessary to pay attention to several aspects related to the wood-glue-FRP interface in order to obtain the best possible results. In fact, a lack of preparation or inadequate preparation of the surfaces could seriously compromise the effectiveness of the reinforcement.

The surface of the wood where the layer is placed must be flat, clean, unadulterated and dry and the temperature must be greater than 10ºC for the whole duration of the drying process.

Numerous studies have been conducted to improve the adhesion by increasing the contact surface area, including:
- sandblasting the surface of the layer and then cleaning it with ethanol;
- the addition to the coating resin of non reactive materials like chalk, clay, powders, etc. which generate little scratches on the reinforcement surfaces;
- liquids like methyl-ketone or toluene in a percentage of weight variable between 30 ÷ 34%, added to the resin before soaking the fibres. Subsequently, during the vulcanisation phase of the resins, these substances generate bubbles of non reactive gas that move around on the nearest strengthening surface where they form micro-scratches.

During the manufacture of innovative test pieces, every effort is made not to vary the normal production process of glulam. During ususal production, the strips are pressed together with a pressure of 690- 1040 KPa for a minimum of 8 hours; in the presence of the reinforcement created by wet preg the layers are pressed at 690 KPa for 22 hours.

In order to carry out mechanical trials the dimensional proportions set out by EN 408[9] are generally observed. In the experimentation under consideration, for the mechanical trials the width varies between 95÷145 mm ,the height between 160÷315 mm and the length between 3,000÷6,700 mm;in the adherence and durability trials the test pieces can have smaller dimensions –the width varies between 30÷85 mm, the height between 30÷120 mm and the length between 90÷1,200 mm .The number of strips varies between 4÷10.

The reinforcement can be positioned according to the patterns shown in figure 1.

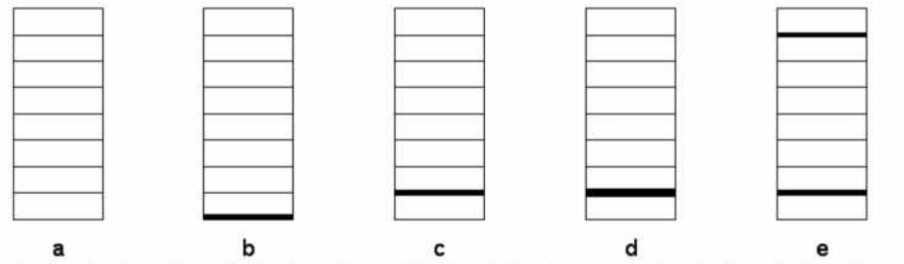


Figure 1: a) not strengthened, b) strengthened in the strained area single exterior, c) strengthened in the strained area single interior, d)strengthened in the strained area double, e) strengthened in the strained area and compressed.

Table 2. Mechanical characteristics of some strengthening systems with FRP in relation to their layout.

DIMENSION (width x depth) (mm)	63,5 x 228.6	63,5 x 228.6	63,5 x 228.6	63,5 x 228.6	63,5 x 228.6	63,5 x 228.6	79,4 x 228.6	79,4 x 228.6
FRP Type and Location	None	AFRP external	AFRP internal	CFRP+ AFRP external	CFRP+ AFRP internal	GFRP+ AFRP external	GFRP+ AFRP external	GFRP+ AFRP internal
INDUCED MOMENT (N*m)	4.425	14.802	11.243	15.286	11.299	14.587	17.350	13.758

Table 3. Mechanical characteristics of beams made of glulam reinforced with GFRP in different positions.

	POSIZIONE DEL RINFORZO	NO RINFORCED	RINFORCED TENSIL AREA	DOUBLE RINFORCED TENSIL AREA	RINFORCED TENSIL AND COMPRESSION AREA
GFRP	**MOE (MPa)**	10.345÷12.824	13.790	13.789	14.134
	MOR (MPa)	41,37	57,6	62,12	54,74

The reinforcements can also be arranged longitudinally:

a. at **partial length**, placed centrally at about 3/5 of the span of the beam and the remaining space filled with wood fibres;
b. at **conventional total length;**
c. at **supposed total length**. The reinforcement is positioned in the strained area and it is strained to approximately 50% of its resistance to tensile stress at the two ends. It is attached to the strips of wood with epoxy resin. Once this hardens the lame is released and it gives strength to the beam that bends.

The maximum load of a conventionally reinforced beam is equivalent to 45 kN, whereas the maximum load of a supposed reinforced beam is double.
The reinforcements can also be arranged transversely:

a. **at partial length**;

b. **at total length**.

The width of the lame influences the resistance to shearing stress.

The applications carried out so far show the indicative values of the strengthening ratio to be $p=A_{reinf}/A_{wood}$, adopted in the test pieces $0.2\% < p < 4\%$.

Table 4. Increases in the mechanical characteristics to the detriment of the strengthening ratio for certain types of wood

			APPARENT MODULUS OF ELASTICITY (MPa)	**MODULUS OF RUPTURE, MOR_{ult} (MPa)**	**ALLOWABLE BENDING STRESS (MPa)**	**DUCTILTY FACTOR, m**	**COMPRESSION FAILURE DEPTH (% depth)**
Western Hem.	**Control**	**Mean**	9108	29,932	9,888	1,4	0%
	1% Rinf.	**Mean**	9729	42,925	13,531	2,4	25%
		Increase	6,4%	30,3%	26,9%	41,7%	100%
	3% Rinf.	**Mean**	10419	54,779	19,499	3,0	48%
		Increase	12,6%	45,4%	49,3%	53,3%	100%
Douglas-fir	**Control**	**Mean**	10281	29,732	10,909	1,2	0%
	1% Rinf.	**Mean**	11178	46,796	15,953	2,0	15%
		Increase	8,0%	36,5%	31,6%	40,0%	100%
	3% Rinf.	**Mean**	12006	57,995	22,722	3,0	35%
		Increase	14,4%	48,7%	52,0%	60,0%	100%

In general, however, it has been established that the best results in relation to the cost/benefit ratio are obtained by $2\% < p < 3\%$. In most of the experiments considered, the fibrous composites are positioned inside the glulam beam between the last and second last strips. The lame has the same width as the beam, but their thickness varies between 2÷4 mm. In these conditions a 2% strengthening ratio present in a beam increases the durability by 50%.

Increases in durability with regard to glulam have been recorded:
- for bending there is an increase of 150%;
- for tensile stress there is an increase of 100%;
- the Coefficient E is increased by 33%.

OTHER METHODS OF STRENGTHENING

Recently, 4 new experimental types of glulam have been made:
- glass fibres placed between the layers of glue;
- Quadralam;
- Armalam;
- Different essences.

Glass fibres between the layers of glue

The usual production process of glulam can easily be supplemented by adding these fibres between the layers of glue, because the fibrous material spreads out between the glued layers without difficulty before pressing, and the excess fibres are cut by the planing machine during the finishing of the components. In the case of single glass fibres (300gr/mq) the coefficient of elasticity can be assumed to be equal to 15.300 N/mmq and the breaking to be equal to 410 N/mmq; however, when the layer is double the coefficient of elasticity can be assumed to be equal to 15.500 N/mmq and the braking equal to 400N/mmq.

Quadralam

This is produced using strips obtained by cutting fibre-reinforced glulam beams; the glass fibre is arranged longitudinally along the beams and then they are glued again to form a grid. In equal sections, both when glass fibres are arranged in the layers of glue and for Quadralam, a material with a high coefficient of elasticity is obtained, 130,000 kg/cmq and 145,000 kg/cmq respectively, with an increase of 30% and 45% compared to the usual.

The average breaking strain is equivalent to 260 kg/cm² for Quadralam and epoxy resin, 437kg/cm² for multilayer Quadralam and resorcin and 644 kg/cm² for Quadralam in Kevlar (AFRP) and resorcin.

The experiments have shown that gluing with resorcin is more effective in comparison to other glues; in particular the epoxy resin bi-component has shown itself to be prone to coming unglued between the "boards", whereas resorcin reinforced with Kevlar (AFRP) fibres has shown the best results and reduced dispersion in the resistance values.

The samples of quadralam, subjected to a resistance to fire test, maintained a complete resistant section, with an area equivalent to 85% of the original for 120'. The normal glulam section, on the other hand, was entirely burned after 80'.

Armalam

This is produced by inserting one or more steel or CFRP bars into special millings made in some of the layers and attached to them with a special epoxy adhesive.

The resulting beam is up to 2.5 times more rigid and up to 2.5 times more resistant. In table 4 a comparison is made between sections of bent beams made of glulam (BS11 and reinforced), on the basis of the equivalent coefficient of elasticity (base x height in cm).

Table 5. Comparison between glulam beams and reinforced beams. (Cp. C. Cattich…)

GLULAM BS 11	10x16.3	10x19.6	12x19.6	14x19.6	14x39.7	16x29.7	16x70.2	20x50.1	20x70.2	20x100.3	20x120.4	20x140.5
ARMALAM	10x12.9	10x12.9	12x12.9	14x26.4	14x29.7	16x19.6	16x50.1	20x36.4	20x50.1	20x70.2	20x86.9	20x100.3

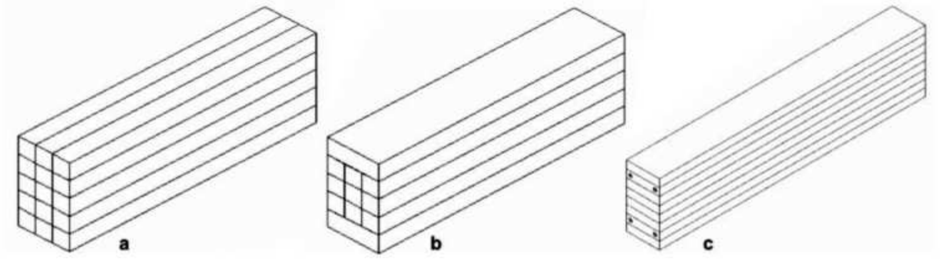
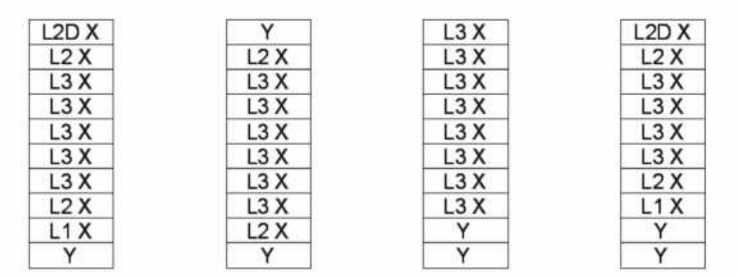


Figure 2 a) simple qudralam; b) multilayer quadralam; c) Armalam.

The use of different essences

The combination of different species of wood inside the beam serves the purpose of improving the mechanical performance, with a reduction in costs. In order to satisfy these requirements various models were made, which are illustrated in figure 5.



L2D X	Y	L3 X	L2D X
L2 X	L2 X	L3 X	L2 X
L3 X	L3 X	L3 X	L3 X
L3 X	L3 X	L3 X	L3 X
L3 X	L3 X	L3 X	L3 X
L3 X	L3 X	L3 X	L3 X
L3 X	L3 X	L3 X	L2 X
L2 X	L3 X	L3 X	L1 X
L1 X	L2 X	Y	Y
Y	Y	Y	Y

Figure 3. The strips marked with the letter Y belong to a species of wood with superior mechanical characteristics compared with the layers marked with X. L1, L2D, L2 and L3 are classified by AITC 401-2005[10].

This method provides for the use of two different species of wood with different mechanical characteristics. In addition, the strips that are made of the same species of wood belong to different resistance classifications.

Performances

The strengthening systems described above were mostly tested to ascertain the durability and mechanical strength of each individual system. As a specific set of regulations does not exist, the regulations for normal glulam were followed, i.e. UNI EN 391:2003[11], ASTM D 1101-92[12] and the instructions given by the American National Standard ANS/AITC A190.1-1992[13]. This states that the maximum de-lamination for soft wood must not be more than 5%, and for hard wood 8%. In the cases considered it can be seen that the de-lamination between the FRP-wood interface depends on the type of adhesive used. In particular, it can be seen that in the case of the adhesive phenolic-resorcinol-formaldehyde, after 5 cycles, the de-lamination is less than the minimum estimate, but widespread small cracks are present; in the case of acid-cure phenolic, the de-lamination after 5 cycles is superior. Other durability tests were being carried out on the adhesives used on the FRP-wood interface, in accordance with UNI EN 302 and ASTM D2559[14].

These durability tests are usually supplemented by mechanical strength tests to check the variations in the state of tension of the reinforced material, both in comparison with the conditions before the durability test, and in comparison with non-reinforced material.

From the study carried out, it has been confirmed that these mechanical strength tests are usually supported and preceded by methods of calculation.

Conclusions

From the data obtained it can be confirmed that carbon and aramide fibres have a superior mechanical resistance to that of wood, and consequently the breaking of beams takes place earlier with wood. Therefore the presence of fibres with very high resistance does not improve the breaking performance; what is more, the increase of the coefficient E is not offset by the increased total cost of the beam.

For this reason, most of the experiments have been directed towards reinforcement with GFRP, some of the obtainable advantages of which are presented. In particular a comparison between the costs of non-reinforced glulam and glulam reinforced with GFRP has been made, for the purpose of establishing the best cost/benefit ratio.

Table 6. Table of cost comparison between reinforced glulam beams and non-reinforced glulam beams with the same mechanical characteristics (cp. A. Dattomi, ... and. A. R. Jordan, ...)

	type of wood	Dim (bxhxl) (mm)	Vol. wood (mc)	Unit cost wood (€/mc)	total cost wood (€)	Unit cost adhesive (€/mq)	total cost adhesive (€)	Dim. Reinf. (bxhxl) (mm)	Unit cost reinf. (€/mc)	total cost reinf. (€)	production cost (€)	total cost beam (€)	saving (€)
no reinf. glulam	pino	180x945 x20.000	3,402	650	2.211	2,65	500	-	-	-	365	3.000	
reinf. glulam	pino	135x1015 x20.000	2,741	450	1.233	2,65	400	Parzial 12.000		150	340	2.000	1.000
no reinf. glulam	Eastern Henlok	3048x524.26 x10.000	15,979	160	2.557							2.557	
reinf. glulam	Eastern Henlok	3048x304.8 x10.000	9,290	160	1.486			3048x6,096 x10.000	4.567	850		2.300	257

It has been found that, given the same mechanical characteristics, the section of the reinforced beams decreases, with a consequent saving of wood equal to 20-40%; furthermore, thanks to reinforcement with fibres, it is possible to use lower quality species, giving an overall cost saving equal to about 25%.

Moreover, the lames of glass fibre are incombustible and form an impassable barrier for the propagation of flames; the temperatures reached when glulam burns are not sufficient to make the fibres lose their mechanical characteristics and they therefore constitute a real support that prevents charred wood from falling; for this reason the stability of the entire structure can be guaranteed, even for very long periods of exposure to flames, without the necessity of enlarging the section of the structures.

From the study carried out, it has been established that one of the limitations of reinforced glulam is the adhesion between the fibres and the wood. For this reason research is being directed towards the application of the reinforcement to a preheated layer, in such a way that the latent heat inside the wood can improve the connection. The systems so far tested with FRP laminated wood appear to yield good results also in terms of cost/benefits. However, the costs of a batch production large enough to make it a competitive product raise a few questions.

Note

[1] With regard to traction stress orientated along the direction of the axis of the fibres, wood is more resistant and more rigid and has an elastic-fragile breaking value. However, for compression stress it is much weaker and has a breaking value roughly equivalent to half that of the traction stress value.

[2] The regulations in force for the classification of wood are: EN14081, EN518, EN519, EN 338, EN1912:2000, UNI 11035 - 1:2003

[3] They are obtained through chemical synthesis. In general they are principally polymers. They are classified in EN 301 and the test methods are described in EN 302.

[4] The recommended values for conifers are shown by the following table from UNI EN 386:
Clamping pressures recommended for conifers

Thickness of the layers *t*, in mm	*t* 35	35<*t* ≤ 45
Pressure in N/mm²	0.6	0.8 with grooves 1.0 without grooves

[5] The only limitation fixed by the regulations is the thickness and the area of the cross section of the individual layers, which is fixed by EN 386 at an interval between 35÷45 (mm) and between 10,000÷12,000 (mm²). Therefore the measurements of the structural components can reach any shape or size, thanks to the combination and gluing of the individual layers.

[6] The de-lamination test regulated by UNI EN 391:2003 "Glued glulam – Test for the de-lamination of the gluing surfaces".

[7] Pultrusione is a slow and expensive process. It involves pulling the fibres through a bath of thermosetting resins where the orientated fibres are added.

[8] Wet preg is a simpler process. The fibres are simply impregnated with a resin in situ.

[9] UNI EN 408:2004 "Wooden structures – Block wood and glulam – The establishing of some physical and mechanical properties".

[10] AITC 401-2005 "Standards for manufactured lumber for use in structural glued laminated timber".

[11] UNI EN 391;2003 "Glued laminated wood – De-lamination test for the gluing surfaces".

[12] ASTM D 1101-92 “Standard Test Methods for Integrity of Glue Joints in Structural Laminated Wood Products for Exterior Use”.

[13] ANSI/AITC A190.1-1996“Structural Glued Laminated Timber”.

[14] ASTM D 2559-00 “Standard Specification for adhesives for structural laminated wood products for use under exterior exposure conditions”, equivalent to UNI EN 302-2:2005. “Adhesives for wooden load bearing structures – Test methods – Establishing the resistance to de-lamination”.

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