

Mechanical characterization of homogeneous and hybrid beech-Corsican pine glue-laminated timber beams

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ABSTRACT

This paper describes the results of an experimental investigation on novel homogeneous and hybrid beech-Corsican pine glue-laminated timber (glulam) beams made of short supply chain timber boards and melamine-based adhesive. The aim is to carry out the mechanical characterization of these glulam beams both in the homogeneous and in the hybrid configuration by four-point bending tests with different span to depth ratios of the specimens in order to differentiate bending and shear tests. The experimental results were fitted analytically as well as by means of Finite Element (FE) numerical simulations. Moreover, the stiffness of these novel beams is further evaluated, with respect to a comparison with a commercial product made of GL24h glulam. The experimental and numerical analysis point out the goodness of hardwood for the manufacturing of glulam beams, even in hybrid configuration in which the inner layers are made of low graded timber boards, with a great opportunity to optimize the raw material.

1. Introduction

In recent times timber has been more and more used in building construction, thanks to its advantages as sawn timber and as engineered wood products. Among the most used products, glue-laminated timber (glulam) and cross-laminated timber (CLT) proved to be competitive with other traditional construction materials, such as reinforced concrete, as studied by Baharimi et al. [1] regarding load-bearing capacity of CLT panels and by Li et al. [2] of bamboo-wood composite CLT. Furthermore, the use of thin wood veneer-based products is developing with respect to the use of thin wood veneer-laminated timber was investigated by Chybiński et al. [3] for structural purposes. The

first application of glulam timber, in Europe, was in the early 1890s and, in 1901, a patent from Switzerland signalled the true beginning of glue-laminated timber constructions. Notwithstanding the long-lasting production in time, glulam must be still considered as an actual composite product, due to the chance to get long sized beams and adopting low quality logs compared to solid beams. Conifers have been by far the most preferred tree species for glulam production due to the lower density compared to hardwoods and a better shape of the logs. The greatest value of conifers was to increase trusting in the glulam composite, giving life to a well-defined product in terms of mechanical performances by varying the environmental conditions in which it could be used; due to such reasons, glulam manufactured from conifers is still much used by building designers. Despite the fact that the employment of timber as

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construction material is beneficial, a more conscious choice of wood origin and application could be more advisable since conifers products are even too much widespread in territories where their presence must be considered historically unsustainable looking to the history and the landscape [4]. From the technological point of view, because of lower density, glulam made of coniferous species is characterized by good workability (sawing, drying, grading, gluing), but also by a reduction in the strength parameters and lower Young's and shear moduli compared to hardwood [5]. In the recent years the use of hardwoods in wooden construction has become a very important topic in Central Europe [6,7], this is because hardwoods have proven to cope better climatic changes and environmental stresses such as they are more soil and climate apt to face strong wind falls, the interest in them is more and more increasing [8]. In the last time the consumer is more accustomed to the use of hardwoods [9] and many attempts of glulam based on hardwood have been made [10]. Among hardwoods, beech is considered one of the most promising species because of its diffusion at European level but currently the use of beech and other species find in energy its preeminent competitive use [11], an intermediate step, e.g. as building material, could add value to this resource [12] and promote the principle of cascade use in wood. Indeed, beech composite products for structural purposes well fit the concept of short supply chain [4], which is one of the pillars of the bioeconomy strategy which has been launched at European and Italian level, sustaining the low carbon economy [13]. The idea of using beech for structural products and glulam is not new, with important researches by Egner and Kolb [14] and later by Gehri [15], Ehrhart et al. [16] and Frese and Blass [17]. Recent studies have demonstrated the high strength of beech engineered wood products such as glulam beams and cross-laminated timber panels [18]. So far beech glulam beams use was restricted by the lack of standards for grading beech lamellae strength, and the absence of design values needed in construction design. Some technical hurdles have now been solved in beech wood grading for structural purposes [19,20] and also bonding has provided fine results [12,21], enabling the exploitation of mechanical properties of the species.

The object of the paper is to present the results of an experimental investigation, concerning the mechanical characterization of glulam beams made of beech (*Fagus sylvatica*) and Corsican pine (*Pinus nigra* subsp. *Laricio*). Two main configurations are studied, the first one consisting in homogeneous beech glulam beams and the second one in hybrid glulam beams with the outer layers of beech and the inner layers of Corsican pine. A total of 28 four-point bending tests was carried out, with different span length to height ratios for the bending and shear tests, according to EN 408 [22].

Moreover, Finite Element (FE) numerical simulations were performed in order to analyse the differences between the experimental configurations and commercial products and to point out the advantages in using hardwood for the manufacturing of glulam beams.

2. Materials & methods

2.1. Characterization of the raw material

The raw material used to manufacture the glulam beams was made of Corsican pine (*Pinus nigra* subsp. *laricio*) and beech (*Fagus sylvatica* L.) boards originated from South Italy (Calabria). The boards had a nominal cross-section of 120 mm width and 20 mm thick, and an average length of 3.10 m (beech) and 4.00 m (pine). The batch of boards was kiln-dried in order to reach the suitable moisture content for the manufacturing gluing process, fixed at 10%.

Before further processing, the dynamic modulus of elasticity of each board was determined by the grading machine ViSCAN-Portable (MiCROTEC). Each board was firstly weighed and measured to determine its density ρ . Then, the natural frequency of vibration f induced by a percussion was measured by using a laser interferometer. The dynamic modulus of elasticity E_{dyn} was thus calculated as:

$$E_{dyn} = \rho (2lf)^2 \quad (1)$$

Where ρ is the density of the board, l is the length and f is the frequency.

The machine settings for the strength grading of beech and pine were developed according to the technical standardization EN 14081-2 [23] in previous studies by Nocetti et al. [24] and Brunetti et al. [25]. The dynamic modulus of elasticity was the main parameter used during the strength grading and the raw material was qualified as D40 and rejects for beech and C20 and rejects for pine according to EN 338 [26].

The 95% of beech boards was graded as D40, while the remaining 5% was discarded mostly because of defects (presence of fiber deviations and not uniform planing). The yields for Corsican pine boards were: 73% graded as C20 and 27% rejected. Totally 210 beech boards and 74 Corsican pine boards were hence used for the production of two series of glue-laminated beams.

Besides, the dynamic modulus of elasticity measured during the strength grading procedure was used to estimate the modulus of rupture (f_m) and the global and local static modulus of elasticity (E_{gl} and E_l respectively) of the raw material. Regression analysis was performed based on destructive tests carried out on beech and pine during the machine setting development. Linear regression expressions were defined by using the E_{dyn} as explanatory variable. The results of the measurements carried out during grading (density and E_{dyn}), and the following estimation of the static properties are summarized in Table 1 with the relative standard deviations s_y and standard errors of estimation $s.e$.

2.2. Glue-laminated beam specimens

Two different series of eight-layered glue-laminated timber beams, made respectively of beech and beech and Corsican pine, were realized to carry out an extended experimental campaign to assess their mechanical properties prior to the industrial production. The hybrid configuration is composed by two beech outer layers and six Corsican pine inner layers. A total of 28, eight-layered glue-laminated timber beams were manufactured at the Pagano S.r.L. factory (Oricola – AQ – Italy).

In order to guarantee the suitable planar surface, preferred for the face gluing, boards were cut to the required length and planed to a thickness of 18 mm. This resulted in a cross-sectional depth of 144 mm for all the specimens. The layering of the boards and the gluing process were performed by machine (Fig. 1 left).

Timber boards were overlapped and glued together by a Melamine Urea Formaldehyde (MUF) adhesive (GripPro™ Design – AkzoNobel, that was obtained by mixing a two component hardener (H002) and a liquid flexible resin (A002)). The choice of employing the melamine adhesive was due to the usage of beech hardwood boards in both homogeneous and hybrid beam's configurations with Corsican pine's boards [27]. In particular, the GripPro™ adhesive is specifically designed for softwood as well as for hardwood timber, such as beech,

Table 1

Mean values of the density (ρ), dynamic modulus of elasticity (E_{dyn}), measured during strength grading and mean values of bending strength (f_m) and local and global modulus of elasticity (E_l , E_{gl}), derived by regression analysis based on E_{dyn} . Standard deviation s_y and the standard errors of estimation $s.e$ are also reported.

Timber species	ρ [kg/m ³]	E_{dyn} [N/mm ²]	f_m [N/mm ²]	E_l [N/mm ²]	E_{gl} [N/mm ²]
Beech	753	16,506	83.1	16,640	15,977
s_y	40	1597	–	–	–
$s.e$	–	–	± 6.1	± 1321	± 1407
Corsican pine	497	9501	37.6	9588	8359
s_y	43	2348	–	–	–
$s.e$	–	–	± 7.1	± 2072	± 1949

Table 2

Size (B = base; L = length; H = height), configuration and test type of the examined glue-laminated timber specimens.

Beam series	Configuration / Timber	Specimen n°	B	L	H	Test type
			[mm]	[mm]	[mm]	
HB	Homogeneous beech	7	120	2800	144	Bending
		7	120	1500	144	Shear
BP	Hybrid beech/ Corsican pine	7	120	2800	144	Bending
		7	120	1500	144	Shear

birch, oak and chestnut. The adhesive was distributed by means of extrusion systems in which the adhesive mixture flows in the form of thin, very fluid and suitably spaced lines, through the orifices of special ducts in which the adhesive is under pressure and is mixed with hardener (in our case in the ratio 2 to 1) (Fig. 1 right). The average of glue grammage was 600 g/m^2 . The adhesive was applied in a factory condition of 25°C , with an environmental moisture of 65%. Formed beams were then cold-pressed for 12 h, with a pressure of 11 bar. No finger joints were forecasted in glue-laminated beams of this experimental campaign.

3. Test methods

In accordance with EN 408 [22], the bending and shear stiffness parameters were evaluated from a four-point bending test setup (Fig. 2).

3.1. Bending and shear tests

The bending test is a four-point bending test over a span length of 18 times the depth (H). The shear test is a four-point bending test over a span length of 9 times the depth (H). In both cases, the specimen is simply supported and loaded symmetrically in bending at two points.

3.2. Test methods and instruments

The experimental setup is composed by an hydraulic jack which spreads the load via a rigid beam fixed under the piston, on two symmetric loading heads (Fig. 3 right). The loading rate was kept fix that was set in $0.003H \text{ mm/s}$, so as to reach the failure configuration after $300 \pm 120 \text{ s}$. All the specimens were simply supported at the ends. In order to minimize the risk of possible local indentations, reaction bearing plates (no larger than one-half the tested piece thickness) were interposed between the supports and the bottom surface of the specimens. Similarly, additional steel load bearing supports were placed also between the loading heads and the top face of the specimens (Fig. 3 left). The deformations w were taken as the average of measurements detected by inductive displacement transducers (LVDT) that were placed on both the faces of each specimen. The experimental campaign was performed in a heated and air-conditioned environment, with about 20°C .

In accordance with EN 408 [22], local and global stiffness parameters were evaluated from the experimental measurement of force and deflections:

$$E_{m,gl} = \frac{l^3 (F_2 - F_1)}{b h^3 (w_2 - w_1)} \left[\left(\frac{3a}{4l} \right) - \left(\frac{a}{l} \right)^3 \right] \quad (2)$$

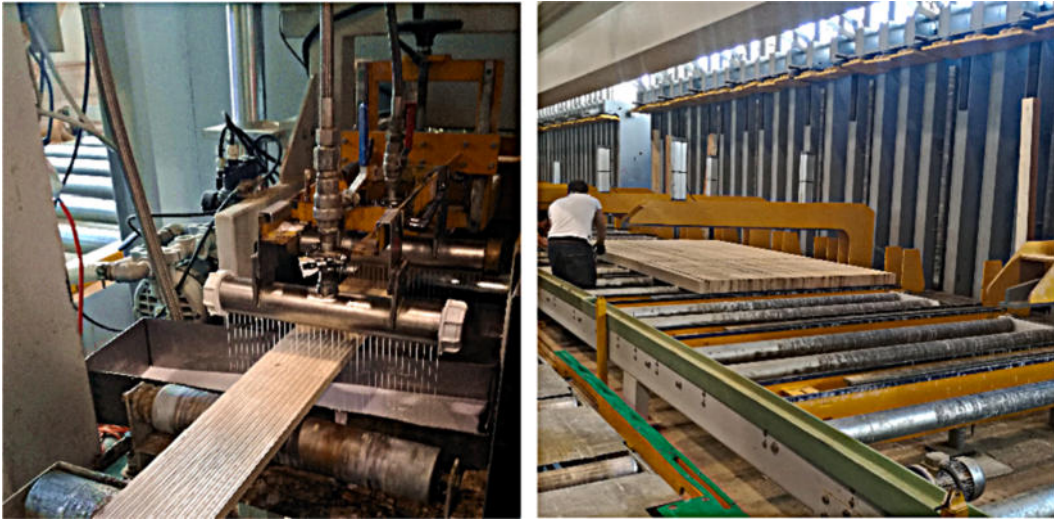


Fig. 1. Glue-laminated timber beams: left) Gluing phase; right) Assembly prior to pressing.

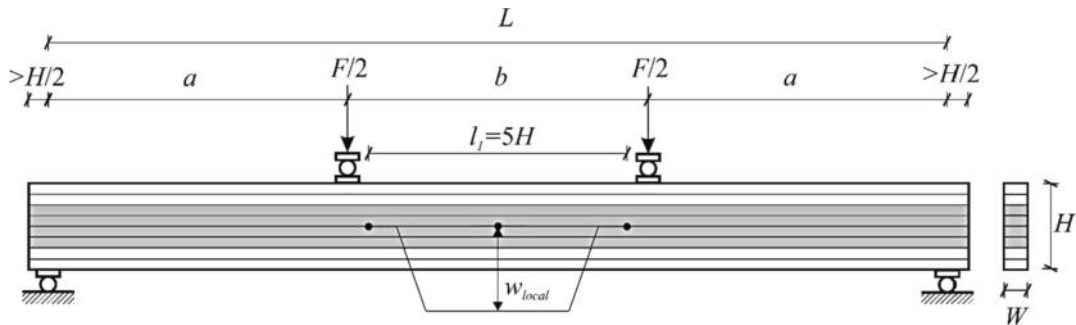


Fig. 2. Test set-up for bending perpendicular to the plane ($a = b = 6H$) and rolling shear test ($a = b = 3H$) [adapted from [22]].

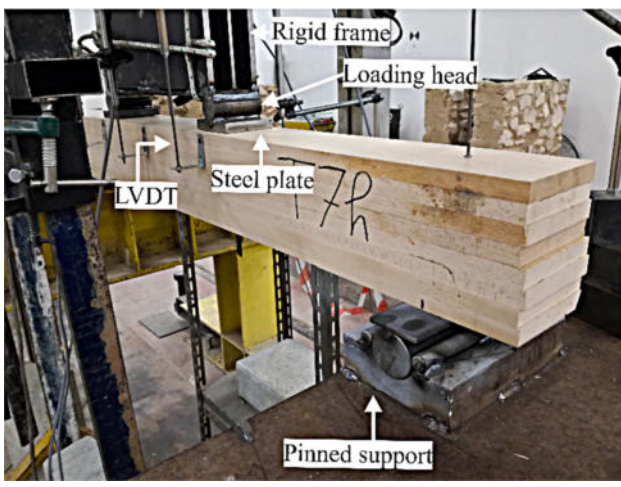


Fig. 3. Set-up left) Equipment details; right) Front view.

$$E_{m,l} = \frac{a^3 l^2 (F_2 - F_1)}{16 I (w_2 - w_1)} \quad (3)$$

with l the length of span in bending, a the distance between the loading heads and the nearest support, b and h are respectively the width and depth of specimen cross section in bending test, I the second moment of area, F_1 and F_2 the 10% and 40% of the ultimate force $F_{\max}$ respectively, and w_1 and w_2 the related recorded deflections.

Based on the theory of elasticity, the flexural (f_m) and the shear (f_v) stresses evaluated at the time of specimen failure is evaluated using the equation:

$$f_m = \frac{a F_{\max}}{2 W} \quad (4)$$

$$f_v = \frac{3 F_{\max}}{4 A} \quad (5)$$

where W is the section modulus and A is the area of rectangular-shaped sections.

4. Test results

4.1. Bending

The results of bending tests are summarized in Table 3.

For each specimen, the flexural stiffness, the bending strength and the failure mode are proposed. Moreover, for both series of beams, the average values, the standard deviation s_y and the characteristic values (5th-percentile) m_k are also estimated according to EN 14,358 [28].

As shown, the most prevalent failure pattern for homogeneous beech beams HB was bending while for hybrid beech/ Corsican pine beams BP was shear failure (Fig. 4).

The load–displacement curves of all specimens, except for HB-4, until the value of load equal to the 40% of the ultimate force $F_{\max}$ are presented both for the homogeneous configuration and for the hybrid one (Fig. 5). The displacement considered is the vertical one at the midspan of the beam. These curves represent the elastic region of the overall behaviour and show how also the hybrid configuration offers good performances in term of stiffness with respect to the homogeneous one.

4.2. Shear

The results of shear tests are summarized in Table 4.

For each specimen, the flexural stiffness, the shear strength and the failure mode are proposed. Moreover, for both series of beams, the

Table 3
Bending test results.

Beam-Specimen n°	$E_{m,gl}$ [N/mm ²]	$E_{m,l}$ [N/mm ²]	$E_{m,gl} I$ [kNm ²]	$F_{\max}$ [kN]	f_m [N/mm ²]	Failure mode
HB –1	14,202	16,672	424	81	42.0	b
HB –2	17,737	20,822	530	106	55.4	b
HB –3	16,852	19,783	503	116	60.2	b
HB –4*	–	–	–	–	–	–
HB –5	16,886	19,822	504	99	51.4	b
HB –6	17,290	20,296	516	107	55.5	b
HB –7	15,954	18,729	476	99	51.7	d
Average	16,487	19,354	492	100	52.7	
s_y	1265	1485	38	12	6.1	
m_k	–	–	–	74	39.3	
BP –1	15,160	17,796	453	93	48.3	s
BP –2	14,304	16,792	427	91	47.2	s
BP –3	15,029	17,643	449	93	48.5	b
BP –4	13,317	15,633	398	89	46.3	s + k
BP –5	14,354	16,850	429	90	46.7	b
BP –6	14,881	17,469	444	90	46.9	s
BP –7	14,757	17,324	441	104	54.5	s
Average	14,543	17,072	434	93	48.3	
s_y	727	854	22	5	2.8	
m_k	–	–	–	81	42.5	

b: bending failure, d: delamination, k: knots influence, s: shear. * omitted due to test instrumental issues.

Where $E_{m,l}$ is the local and $E_{m,gl}$ is the global stiffness parameter, $E_{m,gl} I$ is the flexural stiffness, $F_{\max}$ is the ultimate force and f_m is the flexural stress, s_y is the standard deviation and m_k the 5th percentile.

average values, the standard deviation s_y and the characteristic values (5th-percentile) m_k are also estimated according to EN 14,358 [28]. As shown in Fig. 4, the most prevalent failure pattern for homogeneous beech beams HB was shear, in some cases delamination occurred, while for hybrid beech/ Corsican pine beams BP was shear failure.

As for the bending tests, the load–displacement curves of all specimens, except for HB-6, until the value of load equal to the 40% of the ultimate force $F_{\max}$ are presented both for the homogeneous configuration and for the hybrid one (Fig. 6). Even in these tests the hybrid configuration presents similar performances in term of stiffness with respect to the homogeneous one.

5. Standard comparison

According to § 5.1.3 of EN 14,080 [29], the characteristic strength, stiffness and density properties of glue-laminated timber shall be verified either i) from classifications from layouts and lamination properties

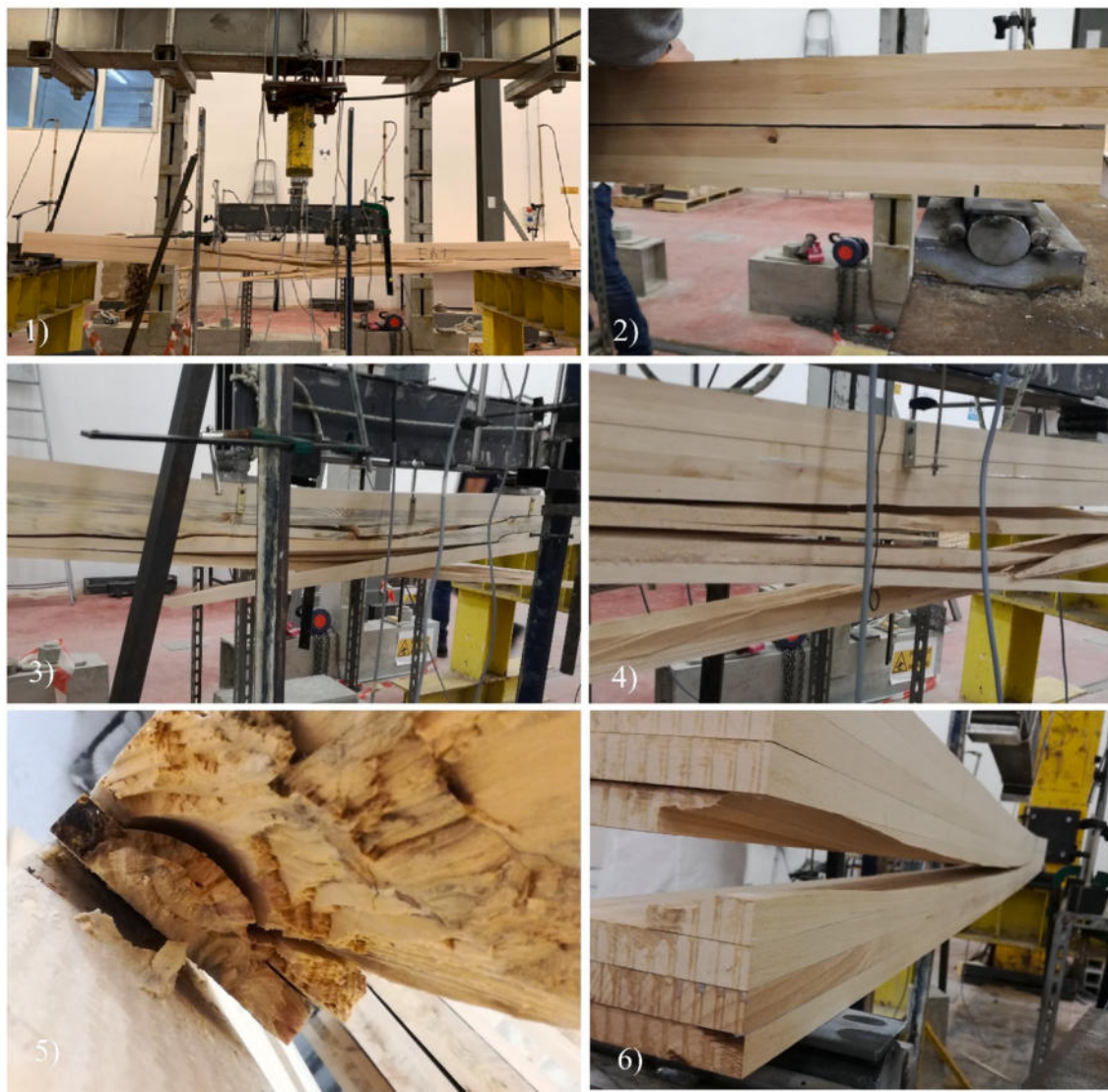


Fig. 4. Details of failure modes of the bending tests: 1), 2), and 3) bending failure modes; 2) and 6) delamination failure modes; 3) and 5) influence of defects.

ii) from calculations taking into account the cross sectional layup and documented properties of boards and finger joints or iii) from full scale tests.

In our case, the characterization and grading of laminations and glulam beams were performed as summarized in Fig. 7.

The Z-9.1-679 is a German provision specifically formulated for beech glulam beams.

5.1. Beam grading

5.1.1. Homogeneous beams

Some novel tensile DT-classes for medium-density European hardwoods (mainly beech and ash) proposed by Kovryga et al. [6], are adopted to define the strength class of homogeneous GLT beams; the mechanical features are evaluated in accordance with the formulations of EN 14,080 [29].

Some of the most influencing parameters on GLT bending strength concerns the material modulus of elasticity and type of lamellas in the tension zone, in particular, on the high-stressed lamellas in the outer tension zone of GLT, while the probability of failure in compression zone can be neglected. So instead of using D-classes, defined for bending applications and developed in relation to bending MOE and strength, these novel DT-classes are formulated with regards to tensile MOE and

are characterized by a higher tensile MOE values parallel to the grain, it would make possible a better exploitation of the hardwood GLT beams behaviour.

Different approaches have been adopted in order to define the strength class, based on the most influential parameters:

1. Based on the machine grading procedure, the beech board class was D40 ($f_{m,k} = 40$ MPa, $f_{t,0,k} = 24$ MPa), as summarized in the previous paragraph; assuming the bending and tensile strength as main parameters (consistently with the previous considerations) a DT24 class was attributed to boards based on the Kovryga et al.'s proposal. Adopting the formulations of EN 14,080 Table 6, the evaluation of the beam class is summarized in Table 5. The formulation for the bending strength was applied by considering the case of board without finger joints and taking, in accordance with the EN 14,080 a characteristic flat wise bending strength of the finger joint as: $f_{m,j,k} = 1,4f_{t,0,1,k} + 12$.
2. Based on the local elastic modulus calculated from the experimental E_{dyn} by linear regressions and density, a DT 46 class was attributed to beech boards ($\rho_m = 750$ kg/m³; $E_{0,mean} = 16500$ MPa). The expressions of EN 14,080 Table 6 were adopted for the evaluation of the beam class. The main mechanical properties of the beams are summarized in Table 6.

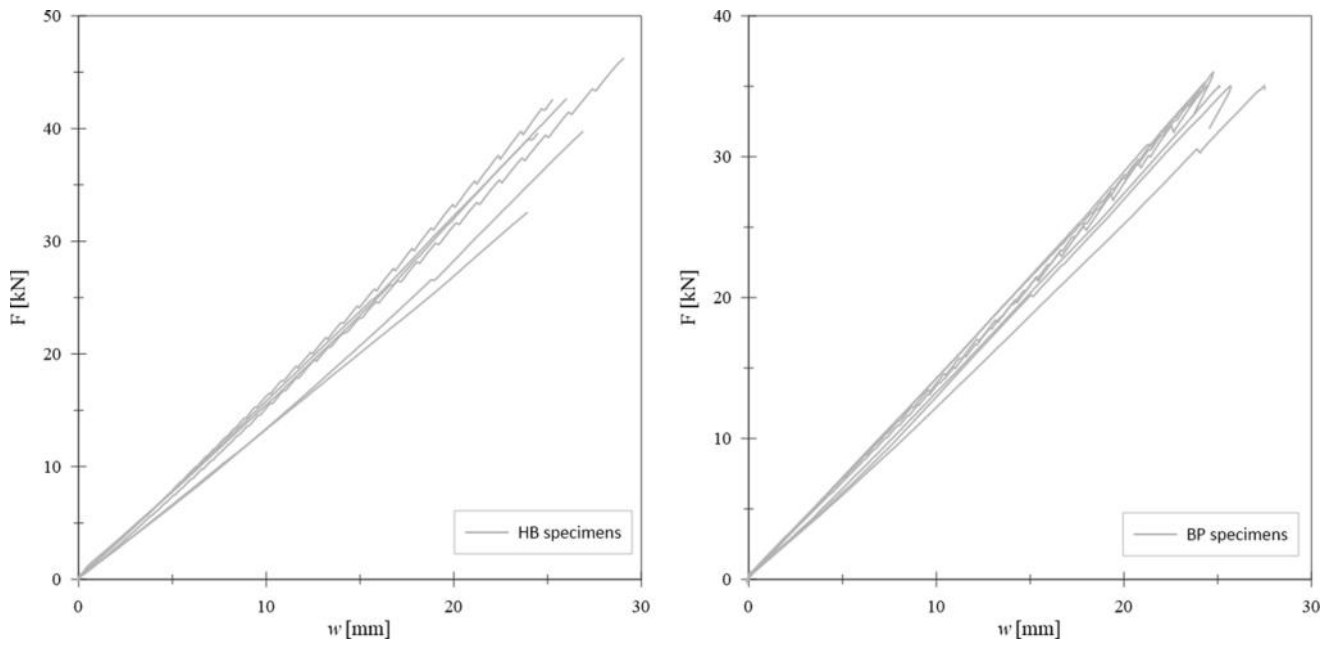


Fig. 5. Load-displacement curves: left) homogeneous beech specimens; right) beech/Corsican pine specimens.

Table 4
Shear test results.

Beam-Specimen n°	$E_{m,gl}$ [N/mm ²]	$E_{m,l}$ [N/mm ²]	$E_{m,gl}I$ [kNm ²]	F_{max} [kN]	f_v [N/mm ²]	Failure mode
HB -1	14,263	16,744	426	156	3.4	s
HB -2	13,808	16,210	412	147	3.2	s
HB -3	16,128	18,934	482	186	4.0	s
HB -4	18,472	21,685	552	225	4.9	s
HB -5	15,272	17,928	456	193	4.2	d
HB -6*	—	—	—	—	—	—
HB -7	13,176	15,467	393	147	3.2	d
Average	15,187	17,828	454	176	3.8	
s_y	1923	2257	58	31	0.68	
m_k	—	—	—	103	2.5	
BP -1	12,299	14,438	367	111	2.4	s
BP -2	12,309	14,449	368	109	2.4	s
BP -3	12,624	14,819	377	116	2.5	s
BP -4	13,803	16,203	412	121	2.6	s
BP -5	13,503	15,852	403	118	2.6	s
BP -6	12,671	14,874	378	125	2.7	s
BP -7	13,463	15,805	402	139	3.0	s
Average	12,953	15,206	387	120	2.6	
s_y	648	760	19	10	0.21	
m_k	—	—	—	97	2.2	

b: bending failure, d: delamination, k: knots influence, s: shear. * omitted due to test instrumental issues.

Where $E_{m,l}$ is the local and $E_{m,gl}$ is the global stiffness parameter, $E_{m,gl}I$ is the flexural stiffness, F_{max} is the ultimate force and f_v is the shear stress, s_y is the standard deviation and m_k the 5th percentile.

- Based on the f_m value calculated from the experimental E_{dyn} by linear regressions, the characteristic value was evaluated ($f_{m,k} = 63.2$ MPa $s_y = 11.2$) a DT 38 class was attributed to beech boards ($f_{m,k} = 61$ MPa) and the expressions of EN 14080 Table 6 were adopted for the evaluation of the beam class. The main mechanical properties of beams are summarized in Table 7.

In Fig. 8 is clearly visible how the adoption of DT 46 class is suitable to fit some of the experimental curves, the main difference in term of stiffness (evaluated considering the curve slope between $0.1 F_{max}$ and $0.4 F_{max}$) is 4%. But it overestimates the characteristic bending strength

of the glulam beam. Experimentally we obtained a 5th percentile of bending strength of 39.3 MPa and a minimum value of 42 MPa (Table 2). In this sense, the values calculated using the strength class of the lamellas (D40 corresponding to a DT24) resulted in a better fit with the experimental achievements, but conservative.

Most likely, the best fitting profile would be the one calculated by the mechanical properties of the lamellas (DT38), assuming that the value of the glulam characteristic strength was penalized by the limited number of tests.

The shear strength tabled and verified experimentally were in line (3.5 MPa vs 3.8 MPa).

5.1.2. Hybrid beams

In accordance with EN 14080 [29], the evaluation of mechanical features such as characteristic bending, the mean modulus of elasticity and the characteristic density of a combined glue-laminated timber shall be determined from the respective values of the different lamination zones considered as homogeneous glue-laminated timber by means of the elastic composite beam theory.

The γ -method proposed in Eurocode 5 is adopted to evaluate the effective bending stiffness of hybrid beams; those latter can be represented as elements made up of different parts mutually connected (Fig. 9). The degree of connection between each part is accounted by the coefficients γ_i which can be equal to 1 for rigid connection or 0 in case of disconnected parts.

The effective bending stiffness is evaluated in Table 8 and 9 as:

$$(EI)_{ef} = \sum_{i=1}^3 E_i I_i + \gamma_i E_i A_i a_i^2 \quad (6)$$

As elastic modulus were assumed as: i) the local modulus of elasticity obtained by using linear regressions from the experimental modulus of elasticity as well as ii) the nominal modulus of elasticity for D40 and C20 class.

In the last decades, many studies have been carried out in order to establish the structural performances of glulam beech beams in combined as well as in the hybrid configuration. The main works were developed by Frese and Blaß [17] and in Z-9.1-679 [30] German provision some class specifically formulated are available for beech glulam beams. In Table 3 of Z-9.1-679 are summarized the six classes developed

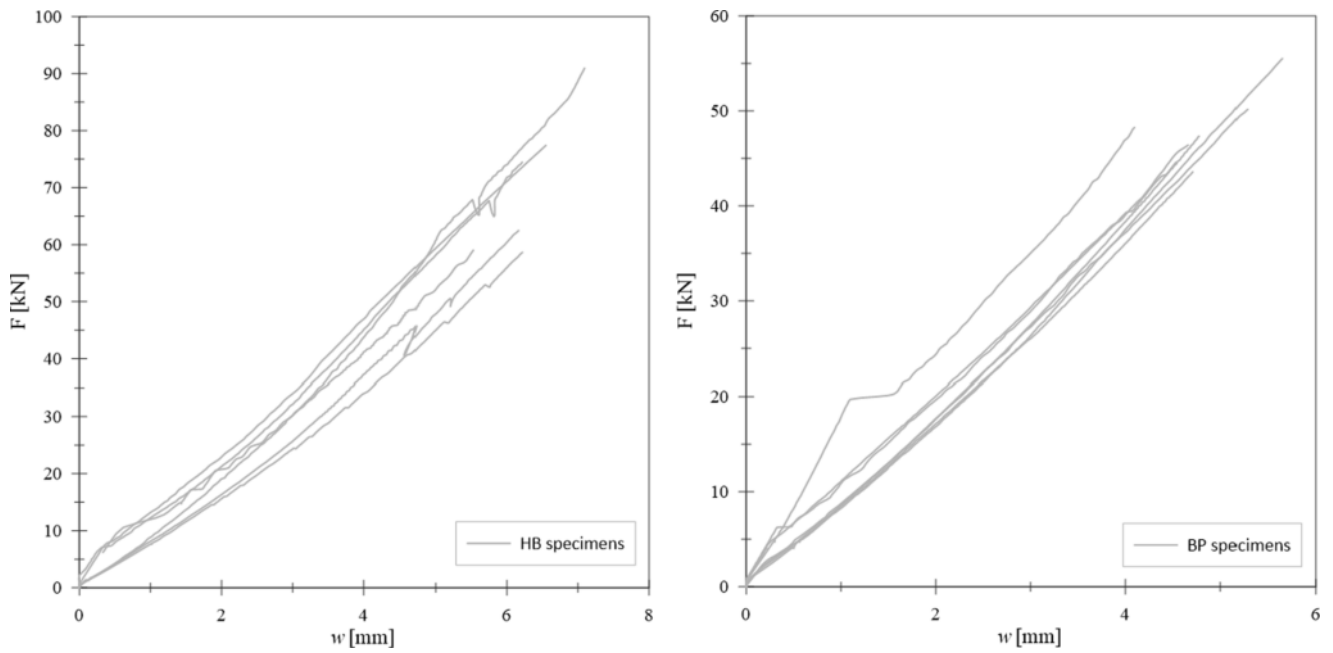


Fig. 6. Load-displacement curves: left) homogeneous beech specimens; right) beech/Corsican pine specimens.

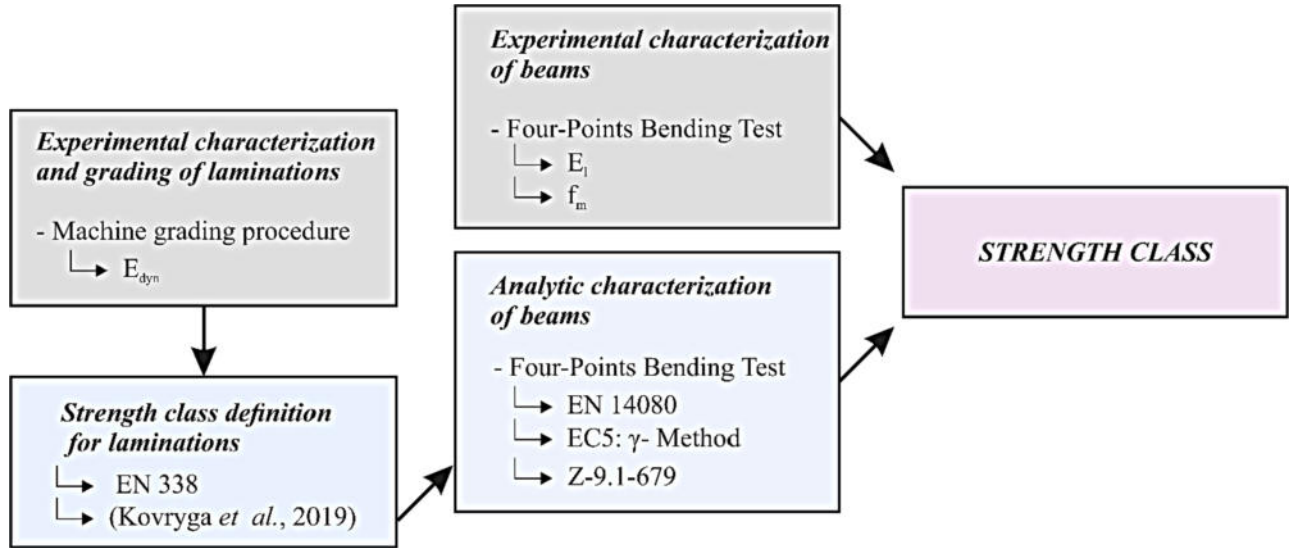


Fig. 7. Chart of characterization and grading procedure of laminations and beams.

Table 5

Homogeneous beech beam features evaluated assuming a board class DT 24.

Homogeneous beech beams		
	Property	
$f_{m,g,k}$	33.5	MPa
$f_{t,0,g,k}$	26.8	MPa
$f_{t,90,g,k}$	0.5	MPa
$f_{c,0,g,k}$	33.5	MPa
$f_{c,90,g,k}$	2.5	MPa
$f_{v,g,k}$	3.5	MPa
$f_{r,g,k}$	1.2	MPa
$E_{0,g,mean}$	14,175	MPa
$E_{90,g,mean}$	300	MPa
$G_{g,mean}$	650	MPa
$G_{r,g,mean}$	65	MPa

Table 6

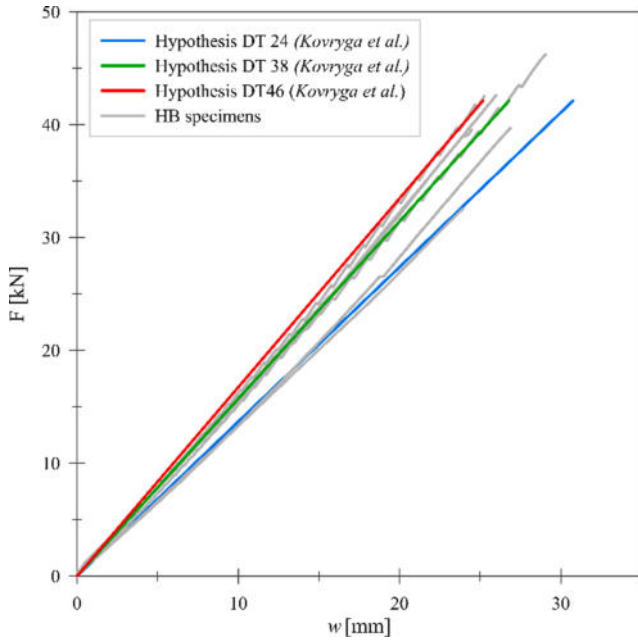
Homogeneous beech beam features evaluated assuming a board class DT 46.

Homogeneous beech beams		
	Property	
$f_{m,g,k}$	50.5	MPa
$f_{t,0,g,k}$	40.4	MPa
$f_{t,90,g,k}$	0.5	MPa
$f_{c,0,g,k}$	50.5	MPa
$f_{c,90,g,k}$	2.5	MPa
$f_{v,g,k}$	3.5	MPa
$f_{r,g,k}$	1.2	MPa
$E_{0,g,mean}$	17,325	MPa
$E_{90,g,mean}$	300	MPa
$G_{g,mean}$	650	MPa
$G_{r,g,mean}$	65	MPa

Table 7

Homogeneous beech beam features evaluated assuming a board class DT 38.

Homogeneous beech beams		
	Property	
$f_{m,g,k}$	44.6	MPa
$f_{t,0,g,k}$	35.7	MPa
$f_{t,90,g,k}$	0.5	MPa
$f_{c,0,g,k}$	44.6	MPa
$f_{c,90,g,k}$	2.5	MPa
$f_{v,g,k}$	3.5	MPa
$f_{r,g,k}$	1.2	MPa
$E_{0,g,mean}$	16,275	MPa
$E_{90,g,mean}$	300	MPa
$G_{g,mean}$	650	MPa
$G_{r,g,mean}$	65	MPa

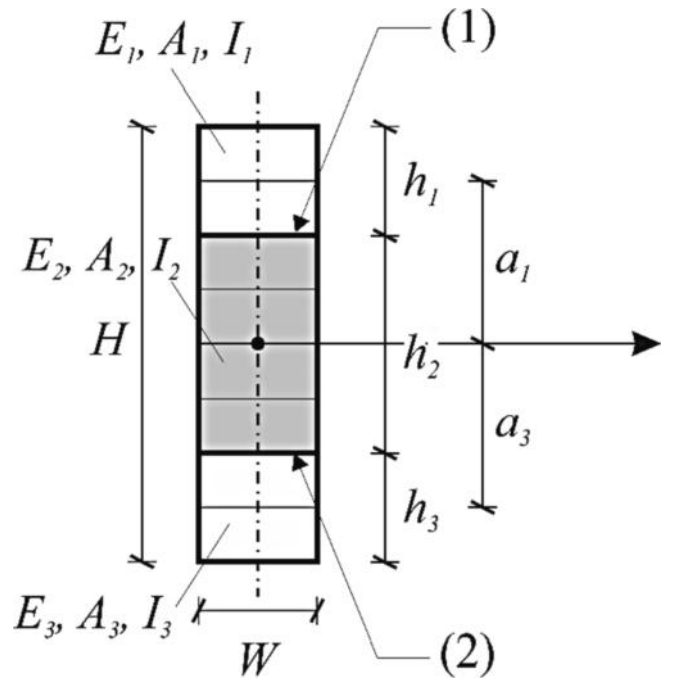
**Fig. 8.** Comparison of load–deflection curve from experimental tests vs hypothetical beam classified as DT24 DT38 and DT46.

for hybrid configuration; the main hypothesis is that i) inner layers of softwood must be visually classified as S10 in accordance with DIN 4074-1 [31] or C24 in accordance with EN14080-1 [29] and DIN 20000-5 [32] and ii) the bending stiffness of softwood finger joints must be $\geq 32 \text{ N/mm}^2$. Satisfying this conditions, the glulam class was defined by knowing the visual classification class (LS13 + E15) and the value of E_{dyn} .

A GL 44 hyb class was assessed and mechanical characteristics defined in Table 5 of Z-9.1-679 [30] are herein summarized ($f_{m,y,k} = 44 \text{ N/mm}^2$, $f_{m,z,k} = 32 \text{ N/mm}^2$, $f_{v,k} = 2.5 \text{ N/mm}^2$, $E_{0,mean} = 14700 \text{ MPa}$).

In both cases, the flexural stiffness was adopted to evaluate the deflection, assuming as load values the experimental one. In Fig. 10 the result of comparisons is graphically represented.

As a result, the comparison with the experimental envelope curve is perfectly fitting with both analytical curves. From the comparison with the curve obtained by applying the γ -method, the scatter in term of stiffness (evaluated considering the curve slope between $0.1 F_{max}$ and $0.4 F_{max}$) is -3.4% , while comparing the curve of GL44hyb class with the experimental one, the stiffness difference is 2% .

**Fig. 9.** Beam cross section for γ -method calculations.

6. Finite elements modelling

6.1. Main purpose

The main aims of the following FE models are: i) defining how a different material's assignment to the model could affect the accuracy of numeric analysis as well as, ii) compare the mechanical performances of the two beam 'series with those of commercial beams made of conifer timber; the hypothesis are to model these latter products assigning the same class of our Corsican pine boards and same geometrical features of our beams and carry on a four-point bending simulation using the software Abaqus/Explicit [33].

6.2. Model description

A comparison in terms of deflection and stiffness of the experimental results with numerical Finite Element (FE) simulations was carried out. Both the homogeneous and the hybrid configurations were reproduced in order to define a well-fitting finite brick-element model. The model reproduces with good accuracy the experimental four-point bending tests setup Fig. 11; in addition to the beam, also the steel ending supports and load plates were introduced in order to simulate the real BCs (hinge and carriage respectively) and the friction conditions between the support surfaces and the bottom of the beam.

An amount of 4655 C3D8R mesh elements, size 22, were used with the structured meshing technique to describe the geometry of the specimens. In the 'property' module timber was modelled as orthotropic elastic material with the definition of different engineering constants and steel as isotropic elastic material. In the hybrid beam model, Corsican pine and beech timber have been assigned after partitioning suitably the beam. Interactions between steel and timber elements were accounted as frictional surface-to-surface contacts with the tangential and normal behaviors described by 'penalty' and 'hard contact' formulations respectively. A static friction coefficient set in 0.3 for steel-to-timber contact and in 0.15 for steel-to-steel contact was applied.

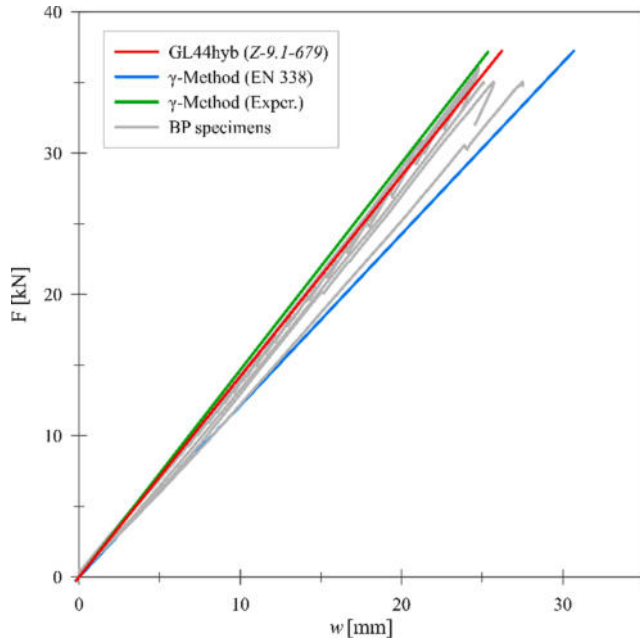
At first, two fitting models were carried on by accounting as beech and Corsican pine elastic and shear modulus thosesummarized in Table 2. Deflections were compared taking as reference point the beam

Table 8Bending stiffness evaluation applying γ -method formulation and EN 338 modulus of elasticity.

Layer n°	h_i [mm]	E_i [MPa]	I_i [mm ⁴]	A_i [mm ²]	γ_i	$a_{1,3}$	a_2	$E_i I_{i,ef}$ [Nmm ²]
1	36	13,000	466,560	4320	1	54	0	1,70E + 11
2	72	9500	3,732,480	8640	1	0	0	3,55E + 10
3	36	13,000	466,560	4320	1	54	0	1,70E + 11
Σ								3,75E + 11

Table 9Bending stiffness evaluation applying γ -method formulation and experimental modulus of elasticity.

Layer n°	h_i [mm]	E_i [MPa]	I_i [mm ⁴]	A_i [mm ²]	γ_i	$a_{1,3}$	a_2	$E_i I_{i,ef}$ [Nmm ²]
1	36	16,440	466,560	4320	1	54	0	2,17E + 11
2	72	9588	3,732,480	8640	1	0	0	3,58E + 10
3	36	16,640	466,560	4320	1	54	0	2,17E + 11
Σ								4,68E + 11

**Fig. 10.** Comparison of load–deflection curves from experimental tests vs hypothetical beam classified as GL44hyb and analytical evidences from γ -method calculations.

center-line (Fig. 12). The FE model fits with great approximation the experimental values leading to an overestimation of the deflection of 7 % for the homogeneous configuration and of 5 % for the hybrid one (Table 10 and 11).

Then, other models for the homogeneous and hybrid configuration respectively were developed with the aim to evaluate how a different material assignment (beams mechanical features instead to laminations features) affects the goodness of FE modelling.

- The model called “*Glulam Beam DT38*” was carried on by assigning to the beam the mechanical properties of a glulam beam (Table 6) evaluated in accordance with EN 14,080 with laminations classified ad DT38;
- The model called “*Glulam Beam GL 44 hyb*” was carried on by assigning to the beam the mechanical properties of GL 44 hyb class defined by Allgemeine bauaufsichtliche Zulassung Z-9.1–679.
- The model “*Glulam Beam DT38*” overestimates the experimental deflection of 10.5% and overestimates the deflection obtained by assigning the proper material to each beam partition (outer and inner beech lamellas) of 4.3%.

- The model “*Glulam Beam GL 44 hyb*” overestimates the experimental deflection of 15.2% and overestimates the deflection obtained by assigning the proper material to each beam partition (outer beech and inner Corsican pine lamellas) of 14.2%.
- Moreover, a comparison between the experimental homogeneous and hybrid specimens and commercial beam was numerically simulated. This commercial product was classified supposing C24 lamellas in accordance with EN 338, in order to have the same class of inner hybrid layers and stress out the advantages of having outer beech layers in hybrid configuration. Due to the lamellas classification, the properties of a homogeneous GL 24 h beam were calculated in accordance with EN 14080.

From the comparison in Table 12 both hybrid and homogeneous beams show a stiffer behavior, leading to a smaller deflection with respect to GL 24 h beams thanks to the contribution of the more performing beech layers. Therefore, this hybrid configuration represents a good example of timber boards optimization and the highlight the excellent performances of beech timber.

7. Conclusions

This paper describes the results, based on experimental tests, analytical analyses and FE modelling, on novel homogeneous and hybrid beech-Corsican pine glue-laminated timber (glulam) beams made of short supply chain timber boards and melamine-based adhesive.

1. The experimental campaign highlights the excellent mechanical performance of the panels, both homogeneous and hybrid. In particular, by analysing the results obtained by the four points bending tests, it emerges that the two configurations have almost comparable performances; the homogeneous beams have reached a maximum force, F_{max} which is 7% higher than the hybrid ones and a flexural stress f_m greater than 8.3 %. Analyzing the failure mechanisms occurred during the bending tests, a greater variability is observed for the hybrid beams rather than for the homogeneous ones, with particular reference to delaminations. Significant differences are observed by comparing the shear performance of the two beams configurations, the homogeneous beams have reached a maximum force, F_{max} which is 31.5% higher than the hybrid ones and a shear stress f_v greater than 31.8 %. Analyzing the shear failure mechanisms, less variability is observed as for homogeneous as for hybrid configuration.
2. In the second part of this work, the goal was to understand whether the EN 14,080 formulations valid for attributing a strength class to beams made with coniferous lamellas can be extended to homogeneous broad-leaved and hybrid products, under which hypotheses and with what results. For homogeneous beams, the tensile DT-



b)

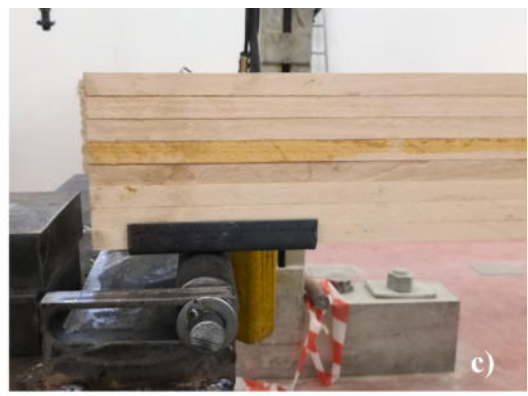


Fig. 11. a) Four-point bending experimental setup, b) FE model beam with ending support and load plates details c) Setup carriage, d) Setup hinge.

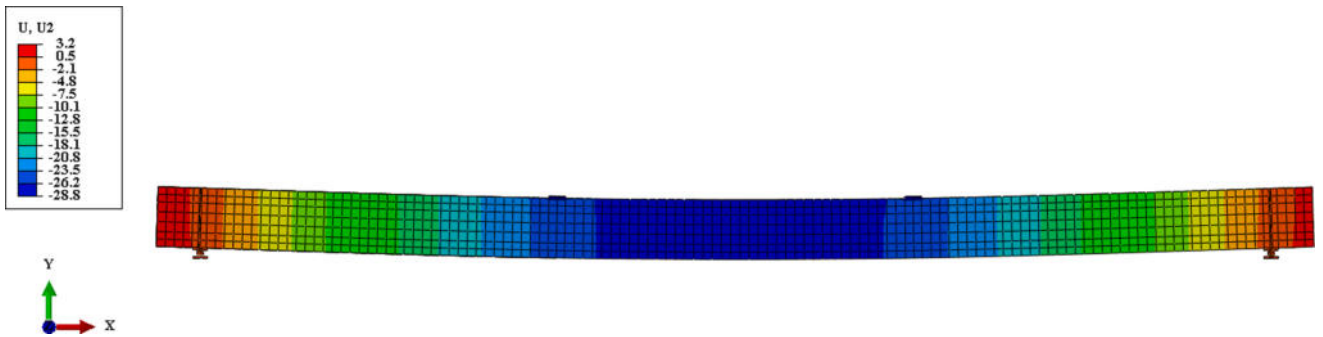


Fig. 12. Vertical deflection (w) for glulam beam GL 44 hyb.

Table 10

Numerical evidences and comparison for homogeneous beams.

HOMOGENEOUS CONFIG.	Test type	E_1 [N/mm ²]	$E_2 = E_3$ [N/mm ²]	$G_{12} = G_{23} = G_{13}$ [N/mm ²]	$0.4 F_{\max}$ [kN]	w [mm]	Δf [%]
	Experimental envelope	–	–	–	39.8	25.5	–
	FE Boards classif. Prop. (beech)	16,440	1165	1040		26.6	–4.3
	Glulam Beam DT38	16,275	300	650		28.2	–10.5

Table 11

Numerical evidences and comparison for hybrid beams.

HYBRID CONFIG.	Test type	E_1 [N/mm ²]	$E_2 = E_3$ [N/mm ²]	$G_{12} = G_{23} = G_{13}$ [N/mm ²]	$0.4 F_{\max}$ [kN]	w [mm]	Δf [%]
	Experimental envelope	–	–	–		25.0	–
	FE Boards classif. Prop. (beech-pine)	16640–9588	1065–639	998–599	34.7	25.2	–0.8
	Glulam Beam GL 44 hyb	14,700	300	650		28.8	–15.2

Table 12

Numerical evidences and comparison with commercial GL 24 h beam.

Material & Configuration Description	Class	E_1 [N/mm ²]	$E_2 = E_3$ [N/mm ²]	$G_{12} = G_{23} = G_{13}$ [N/mm ²]	$0.4 F_{max}$ [kN]	w [mm]	Δf [%]
Homogeneous Commercial Conifer	GL 24 h	11,500	300	650	34.7	33.4	
Tested Hybrid beech/Pine	GL 44 hyb	14,700	300	650		30.7	−8.7
Tested Homogeneous beech	–	16,275	300	650		28.2	−18.4

classes for medium-density European hardwoods (mainly beech and ash) proposed by Kovryga et al. [6] were adopted. In order to define what parameters are more suitable to attribute the glulam class, three different hypothesis have been carried out choosing the bending and tensile strength, the bending stress and the dynamic modulus of elasticity respectively. By comparing the experimental evidences with the analytical ones that the DT38 class (based on the closer dynamic modulus of elasticity) was the best choice. For the hybrid beam, the γ -method and the Z-9.1–679 [30] German provision were adopted. This latter choice allowed attributing a GL44h class to our hybrid beam which fitted with great accuracy the experimental test.

3. At last, a FE modelling was provided in order to compare our products with the commercial one (classified supposing C24 lamellas in accordance with EN 338, in order to have the same class of inner hybrid layer). The strength classes previously attributed were reproduced in the FE models as assigning to each lamellas the right material features, as well as by modelling the whole beam with its own class. From the comparison in terms of deflections it was evident that the hybrid and homogeneous beams could experience a smaller deflection for the same amount of load rather than the conifer beam.

From the results of this work is possible conclude that:

- a) The classification of the lamellas and the accuracy of this procedure is fundamental for the right attribution of strength class of the beams. The setting up of classification rules for species that are still little used should be preferred in order to broaden them knowledge and possibilities of use.
- b) Experimental tests clarified that hybrid and homogeneous hardwood glulam beams have high mechanical performances, so, further investigations could be useful to have a wider comprehension of other species of hardwood timber as well as to fix some points in the open field of adhesives and gluing methods involving hardwood lamellas.
- c) It has been demonstrated that, under the previous hypothesis, is still possible to adopt the EN 14,080 formulations valid for conifer glulam beams also for the definition of the features of hardwood beams. However, adopting the mechanical parameters suggested by EN 338 leads to a considerable underestimation of the beam stiffness. For hybrid products, the strength classes proposed in the German provision Z-9.1-679 [30] as well as the γ -method with the experimental values of timber coming from the board classification allow to fit with good accuracy of the specimens experimental stiffness.

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Credit authorship contribution statement

Martina Sciomenta: Conceptualization, Methodology, Formal

analysis, Formal analysis, Supervision, Investigation, Writing – review & editing. **Luca Spera:** Formal analysis, Writing – review & editing. **Alfredo Peditto:** Investigation. **Edoardo Ciuffetelli:** Investigation. **Francesco Savini:** Investigation, Formal analysis. **Chiara Bedon:** Methodology. **Manuela Romagnoli:** Supervision, Funding acquisition, Writing. **Michela Nocetti:** Timber Characterization, Supervision, Conceptualization, Funding acquisition. **Michele Brunetti:** Timber Characterization, Funding acquisition. **Massimo Fragiaco:** Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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