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Mechanical characterization of five species of Italian bamboo

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Abstract

High mechanical performance coupled with sustainability gives to bamboo a high potential to substitute conventional construction materials in various applications. In particular, there are countries in which this material has been used in construction for millennia and represents an asset, on the contrary, there are countries where there is still not enough knowledge of the structural properties of locally-grown bamboo. In these cases, it is important to extend the knowledge of the mechanical properties of local bamboo species supported by the development of suitable standardised testing procedures. In this view, the paper presents the results of an experimental study for the mechanical characterization of five bamboo species cultivated in Italy (*Phyllostachys bambusoides, edulis, iridescens, violascens* and *vivax*). For compressive tests, the used methodology is compliant with ISO Standards; for tensile test, the procedure suggested by ISO is very difficult to apply so different set up have been proposed and in the second part of the paper a critical discussion about ISO methodology and its possible improvements are reported. The findings from this research shed light on current challenges and on the possible future steps for a wider uptake of natural materials in constructions.

Keywords:
Bamboo, Mechanical properties, Compression test, Tension test, ISO Standards, Phyllostachys bambusoides, Phyllostachys edulis, Phyllostachys iridescens, Phyllostachys vivax, Phyllostachys violascens.

List of symbols

Symbol	Description	Unit
A	cross-sectional area of the culm calculated as $(\pi/4)[D^2-(D-2\delta)^2]$	mm^2
δ	the wall thickness	
b	width of tension test specimen in gauge region	mm
D	outer diameter of the bamboo culm	mm
$E_{c,0}$	compressive modulus of elasticity parallel to fibers	MPa
$E_{t,0}$	tensile modulus of elasticity parallel to direction of fibers	MPa
F	load applied in test	N, kN
F_{ult}	maximum (ultimate) load applied in test	N, kN
$\sigma_{c,0}$	compressive stress in the direction of the fibers during compression test	MPa
$\sigma_{c,0\ 20}$ $\sigma_{c,0\ 60}$	$\sigma_{c,0}$ at 20% and 60% of the ultimate force, respectively	MPa
$f_{c,0}$	compressive strength parallel to direction of fibers	MPa
$\sigma_{t,0}$	tensile stress in the direction of the fibers during tension test	MPa
$\sigma_{t,0\ 20}$ $\sigma_{t,0\ 60}$	$\sigma_{t,0}$ at 20% of the ultimate force, $\sigma_{c,0}$ at 60% of the ultimate force, respectively	MPa
$f_{t,0}$	tension strength parallel to direction of fibers	MPa
ε_z	longitudinal strain in the direction of the fibers	-
$\varepsilon_{z\ 60}-\varepsilon_{z\ 20}$	ε_z correspondent to 60% and to 20% of the ultimate force, respectively	-
ε_t	circumferential strain	-
$\varepsilon_{t\ 60}-\varepsilon_{t\ 20}$	ε_t correspondent to 60% and to 20% of the ultimate force, respectively	-
L	length of test piece	mm
m_i	initial mass of test specimen	g
m_0	oven-dry mass of test specimen	g
ρ	density	Kg m^{-3}

1. Introduction

Construction engineering is increasingly challenged with using eco-sustainable resources by employing raw materials permitting waste and pollution reduction. In this regard, the exploitation of renewable natural materials are particularly suitable as possible substitutes of materials conventionally used (Maraldi, Molari, Regazzi, & Molari, 2017; Mazhoud, Collet, Pretot, & Lanos, 2017). The plant of bamboo is one of the more effective resources which satisfy the requirement of green material for several reasons: its amazing rapid grow, its low embodied energy (De Flander & Rovers, 2009; van der Lugt & van den Dobbelsteen, A Janssen, 2006), its worldwide spreading and its excellent mechanical strength in respect to density (Janssen, 1981). In some Asian, Latin-American and African countries bamboo culms are

traditionally used as beams and columns (Kaminsky & Lawrence, 2016; Minke, 2012; Yu, Chung, & Chan, 2005). Furthermore, the bamboo culms may be also used to realize engineered products, such as laminated composites and scrimber (Sharma, Gatoò, Bock, & Ramage, 2015; Verma & Chariar, 2012).
Mechanical characteristics of several species of bamboo grown in subtropical regions are studied, together with their relationship with the anatomical meso-structure: *Phyllostachys pubescens* (Chung & Yu, 2002; Dixon et al., 2015; Dixon & LJ, 2014), *Guadua angustifolia Kunth* (Alarcon Gutierrez & Olarte Florez, 2013; Archila-Santos, Ansell, & Walker, 2014; Dixon et al., 2015; Gonzalez Quevedo, 2006) *Bambusa stenostachya* (Dixon et al., 2015), *Bambusa pervariabilis* (Chung & Yu, 2002), *Bambusa vulgaris* (Awalluddin et al., 2017; Mat Zain, Ali, & Hussim, 2018), *Schizostachyum grande* and *Gigantochloa scortechinii* (Awalluddin et al., 2017). On the contrary, a systematic investigation of the structural properties of the species growing in temperate climate is rather limited. First studies on *Phyllostachys viridiglaucescens* and *Phyllostachys edulis* are reported in (Fabiani, 2014; Greco, Molari, & Maraldi, 2019).
To promote the use of bamboo in engineering in those countries where it is not regarded as a structural material, an accurate experimental investigation about its mechanical performances is necessary.
The first aim of this paper is the characterization of five species of Phyllostachys, a bamboo family increasingly growing in Italy: *Phyllostachys bambusoides*, *Phyllostachys edulis*, *Phyllostachys iridiscens*, *Phyllostachys violascens* and *Phyllostachys vivax*. The objective is also to identify the species having the best structural performances or the species which are more adapt to be engineered.
The experimental investigations are carried out, as far as possible, according to the standard ISO 22157-1:2019 “Bamboo structures - Determination of physical and mechanical properties of bamboo culms - Test methods”.
Carrying on the tests, it was clear that the compression test suggested by ISO standard was effective and easy to perform while tensile test was not effective and hard to perform.
In general, and in particular in bamboo specimens, tension tests (parallel to the fibers) are more difficult than the compressive characterization since several issues can affect the tensile test results. Fiber gradation across the thickness and ancorage conditions of the specimens influence the strength and the failure. (Richard & Harries, 2015). Moreover, the geometry of the specimen is always very complex (being a curved shell) often-presenting natural flexure and twist; further, the friction coefficient of the outer and inner surfaces of the culm are considerably different, due to both the higher hardness of the outer surface and to the presence of a sort of natural polymeric vax covering it [Nayak, 2016]. Moreover, great tensile longitudinal force needed at failure, may not be associated with a sufficient strength in the radial direction, required to sustain the compressive force generating by the jaws often leading to a premature crushing in the grip area.
ISO 22157 dates back in 2004 [ISO22157-1:2004] and the set up suggested for tensile test in the first release was the traditional dog bone specimen [ISO22157-2:2004]. The new release published in 2019 [ISO22157:2019], specifies a new set-up for tensile test, whose main novelty is the geometry of the specimen: a stick with rectangular cross section with a dimension equal to the culm wall thickness, δ, and width, b, equal to one-half the culm wall thickness or less.
The norm also suggests a reliable interposition of soft wood tabs between the sample and the jaws. This interposition is extremely difficult due to the small-involved area of the specimen and the low adhesion of the bamboo with soft wood.
Performing the tests with this standard is very hard, mainly for bamboo having relatively small wall thickness, like the Italian ones, due to the small area of the specimens.
The second aim of the paper is to point out the problems which arise performing tensile tests on bamboo specimens and to propose some different set up able to mitigate the drawbacks.

The paper is organized in two parts. The first part shows the results of the mechanical characterization, in compression and tension, of five bamboo Italian species:
(i) The compression tests are carried out following ISO 22157:2019, strictly.
(ii) For tension test a set-up, suitable for thin-thickness Italian bamboo, is proposed.
The second part of the paper is dedicated to
(i) discuss critically some aspect of the methodology proposed in ISO 22157:2019 for tensile tests;
(ii) describe the modifications of the experimental rig we adopt to improve the execution of tension test;
(iii) compare the results obtained followimg the different set-up.

2. Mechanical Characterization of Italian bamboo

2.1 Materials

This study enrolls five species of Italian bamboo of the family of Phyllostachys: *Bambusoides (BAM)*, *Edulis*, *Iridescens (IRI)*, *Vivax* (VIV) and *Violascens (VIO)*. All the tested bamboo culms were cultivated in Italy, in particular *Bambusoides*, *Iridescens*, and *Vivax* in Langhe (Piemonte region, north-west part of Italy), *Edulis* in Pordenone, (Friuli Venezia Giulia, north east part of Italy), and *Violascens* in Bologna, Emilia Romagna.
Two parts of one meter length are cut from the culm: the first one from 0.5 to 1.5 m from the ground (identified as 'BOT') and the second one from 2.5 to 3.5 m from the ground (identified as 'TOP'). From each of the two parts of a culm, 4 specimens are obtained: two cylinders for the compressive test, one with node and another one without node and two sticks of rectangular cross section for the tension test, one with node and one without node. Three culms for each species are examined. The cylindrical specimens for compressive test are cut from the culm using a circular saw. The stick specimen for the tensile test are obtained using a splitter.
Humidity and density are measured as suggested by ISO 22157:2019 for each tested culm.

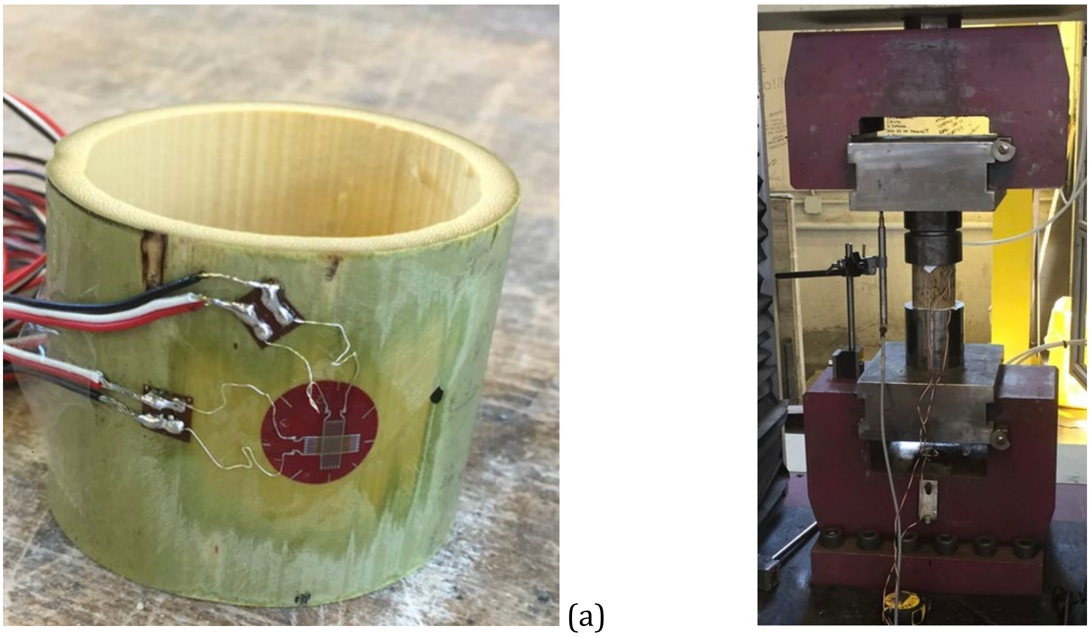
2.2 Experimental set-up

2.2.1 Compression test parallel to the fibers

The dimensions of the specimens were established and measured in accordance with ISO (Bamboo structures - Determination of physical and mechanical properties of bamboo culms - Part 1: Test methods) such that $L<D$ or $L < 10\ t$, being L the height of the specimen, D the external diameter and δ the thickness of the culm specimen.
The tested specimens were equipped with two orthogonal bidirectional strain gauges as shown in Figure 1a to measure the deformation in the direction of the application of the load (parallel to the fibers) called ε_z and in the circumferential direction named ε_t.
Loading has been provided by means of a hydraulic press universal machine (METROCOM, 600 kN maximum static capacity), in displacement control, with an imposed displacement velocity of 0.3 mm/minute. A linear variable displacement transducer (LVDT) HBM 1-WA/50MM-T was used to measure vertical displacement. The upper plate of the press is provided by a spherical joint to mitigate a possible uneven load distribution on the sample cross-section. A layer of Teflon tissue of extremely low thickness was interposed between the specimen and the load plates, in order to limit friction.
The normal stress, $\sigma_{c,0}$, in longitudinal direction and the compressive strength $f_{c,0}$ are:

$$\sigma_{c,0} = \frac{F}{A},$$
$$f_{c,0} = \frac{F_{ult}}{A},$$

respectively, being A the nominal area of the circular crown of the cross section of the culm, F the force imposed by the press machine.



(a) (b)

Figure 1. Compression test: (a) specimen equipped with a bidirectional strain gauge, (b) set up.

Assuming a linear elastic constitutive law and a homogeneous state of strain, it was possible to recover the longitudinal Young modulus and the ratio between the transversal and longitudinal deformation.
As suggested by ISO, the Young modulus was calculated in the interval between 20% and 60% of the maximum stress:

$$E_{c,0} = \frac{\sigma_{c,0\ 60} - \sigma_{c,0\ 20}}{\varepsilon_{z\ 60} - \varepsilon_{z\ 20}}$$

being $\sigma_{c,0\ 60}$ and $\sigma_{c,0\ 20}$ the stress at 60% and at 20% of the ultimate normal stress, respectively, and $\varepsilon_{z\ 60}$, $\varepsilon_{z\ 20}$ the related longitudinal strains.
The same interval is chosen to calculate the Poisson ratio between tangential and longitudinal deformation:

$$r = -\frac{\varepsilon_{t\ 60} - \varepsilon_{t\ 20}}{\varepsilon_{z\ 60} - \varepsilon_{z\ 20}}$$

being $\varepsilon_{t\ 60}$, $\varepsilon_{t\ 20}$ the transversal strains correspondent at 60% and at 20% of the maximum stress.

2.2.2 Tension test parallel to the fibers

To overcome all the difficulties faced proceeding with the set up suggested by ISO (Bamboo structures - Determination of physical and mechanical properties of bamboo culms - Part 1:

Test methods), a different first set up to characterize the 5 bamboo species is assessed (in the second part of the paper a discussion about the ISO 22157:2019 standard prescriptions for tensile test is reported with other possible solutions).
Each specimen is prepared splitting a bamboo stick of cross section with breadth equal to the culm wall thickness of the culm δ and the width, b, equal to 5 mm. The stick is then buried at the extremities in an aluminium pipe filled by resin. For centring the stick and sealing the resin two hollow cylindrical shaped rubber seals are posed at the two ends of the piece of pipe as shown in Figure 2. An epoxy resin (SIKADUR®-330) is filled from bottom to top, using a 100 ml syringe by two holes drilled in each aluminium tube (as shown in Figure 3). The specimen is then dried for 24-hour at room temperature.

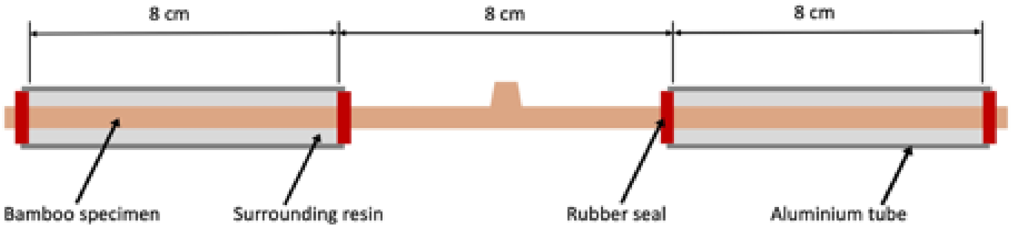


Figure 2. Sketch of the specimen.

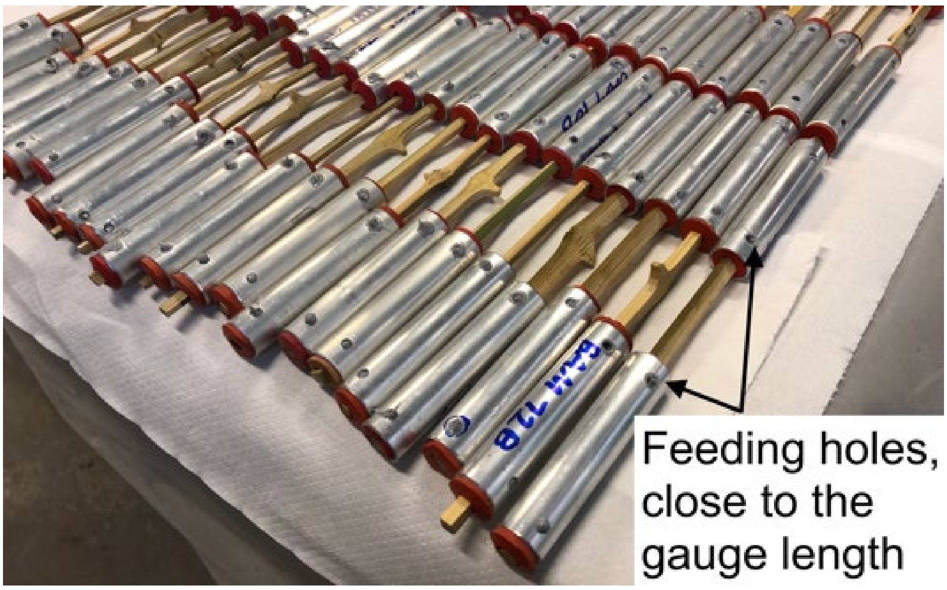


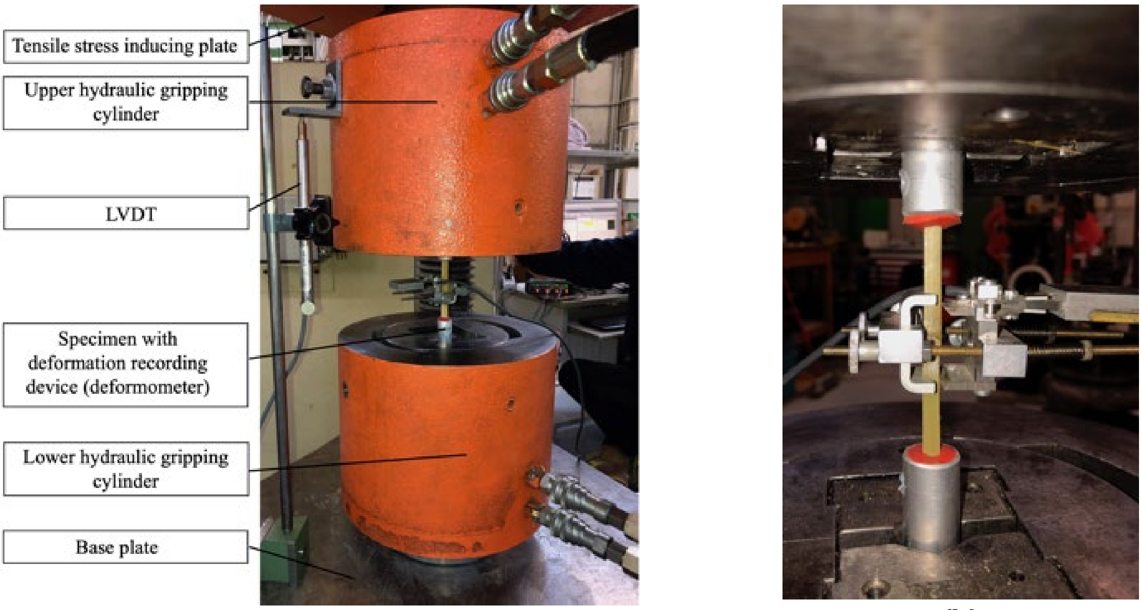
Figure 3. Tension specimens.

The testing set-up is shown in Figure 4(a). The load is applied through universal testing machine GALDABINI, with maximum capacity of 100 kN. A DD1 HMB estensometer was installed directly on the specimen, holding on to the sides of it, as shown in the close-up of Figure 4(b). To monitor the displacements between the jaws, an additional LVDT HBM 1-WA/50MM-T was installed.
The normal stress in the direction of the load $\sigma_{t,0}$ was calculated considering the area A as suggested by ISO 22157:2019. The longitudinal strain ε_z was measured by the estensometer.
Assuming a linear elastic constitutive law, the longitudinal Young modulus was calculated (as suggested by ISO 22157:2019) as:

$$E_{t,0} = \frac{\sigma_{t,0\,60} - \sigma_{t,0\,20}}{\varepsilon_{z\,60} - \varepsilon_{z\,20}}$$

The value of the tensile strength was calculated at the maximum loading force as

$$f_{t,0} = \frac{F_{ult}}{A}$$



(a) (b)

Figure 4. Tension test: (a) experimental set-up, (b) zoom on the specimen with estensometer.

2.3 Results

2.3.1 Initial dimensions and density of the culms

The mean value and the standard deviation of the external diameter *D*, of the thickness δ and the density ρ of the culms are reported in Table 1. The mean diameters span from 51.13 mm, for *VIO*, to 79.43 mm, for *Vivax*. The thickness goes from 4.53 mm of VIO to 7.25 mm of EDU (which shows a very thick culm at the bottom in respect to the upper part).
The density is comparable for BAM, EDU and IRI, while lower values have been found for *VIO* and *VIV*. For all the species, the density of the TOP specimens is higher than the BOT ones, except *BAM* for which the two values are similar.

Species		***D* [mm]**		**δ [mm]**		**ρ [kg m^{-3}]**		**n. culms**
		Mean	*St.Dev*	*Mean*	*St.Dev*	*Mean*	*St.Dev*	-
BAM	TOP	58.06	3.25	4.70	0.55	875	6	6
	BOT	58.67	2.96	5.95	0.41	891	43	6
	ALL	58.36	2.98	5.33	0.80	883	29	12
EDU	TOP	62.42	3.88	5.81	0.59	918	67	6
	BOT	71.78	0.84	8.69	0.79	898	55	6
	ALL	67.10	5.57	7.25	1.65	908	56	12
IRI	TOP	62.07	2.30	5.74	0.31	887	36	6
	BOT	61.73	3.18	7.83	1.10	832	29	6
	ALL	61.90	2.65	6.78	1.34	860	42	12
VIO	TOP	46.18	4.15	3.94	0.19	762	9	6
	BOT	56.08	3.31	5.11	0.33	724	52	6
	ALL	51.13	6.29	4.53	0.67	743	39	12

VIV	TOP	77.67	8.88	5.49	0.81	790	19	6
	BOT	81.19	6.70	7.10	0.44	751	22	6
	ALL	79.43	7.72	6.29	1.05	770	28	12

Table 1. Mean value, standard deviation of diameter, thickness and density of the specimen used in compressive tests.

2.3.2 Compressive test parallel to the fibers

Figure 5 shows longitudinal compression stress versus longitudinal strain (negative values) and versus circumferential strain (positive values) for all the specimens tested for *BAM*. All the other species show the same behaviour.

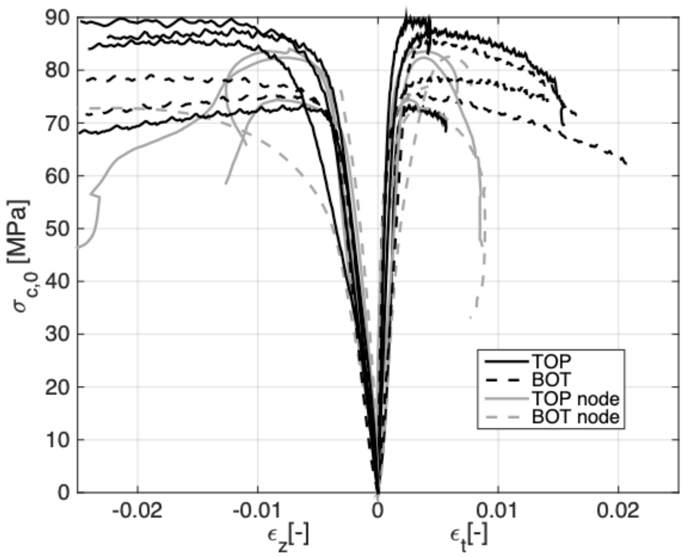


Figure 5. Compression test: examples of stress versus longitudinal and circumferential strain for *BAM* species.

The graph reveals an initial linear stress-strain relationship followed by a non-linear behaviour. The mean values and standard deviation of the ultimate compressive stress, of the Young modulus, of the ratio between the transversal and longitudinal strains and of the water content are collected in Table 2.

Species	$f_{c,0}$ **[MPa]**		$E_{c,0}$ **[GPa]**		r **[-]**		w **[-]**	
	Mean	*St.Dev*	*Mean*	*St.Dev*	*Mean*	*St.Dev*	*Mean*	*St.Dev*
BAM	80.43	6.75	20.34	5.02	0.34	0.17	9.60	0.79
EDU	68.69	8.06	14.04	3.64	0.27	0.10	10.84	0.30
IRI	80.12	5.00	21.89	3.99	0.35	0.20	10.38	0.39
VIO	59.50	7.26	16.27	5.71	0.47	0.28	10.15	1.50
VIV	64.35	2.80	17.37	2.61	0.39	0.15	10.11	0.23

Table 2. Compression test: mean values and standard deviation for each species considering all the tested specimens

Performing a statistical analysis using the Matlab tool Anova

Figure 6 shows the box plot of compressive strength, Young modulus and Poisson ratio of the different species. The analysis of Variance conducted by using Matlab tool Anova shows that for compressive strength BAM and IRI are significative different from EDU VIV and VIO.

For Young modulus BAM, EDU and VIV do not behave in a significantive different way in respect to other species. IRI behaves differently from VIO.
For Poisson ratio the species do not show significantly differences.
Four failure modes are encontered:

1) expansion of the central part of the specimen (Figure 7a),
2) expansion of the bottom and upper part of the specimen (Figure 7b),
3) expansion of only one part (the upper or the bottom) (Figure 7c),
4) a local buckling (Figure 7d).

In all the case there is a local crush of the specimen (Figure 7e) in the part of the specimen in contact with the loading plates which can, in some cases, lead to a separation of the outer skin of the bamboo (Figure 7f). In cases where the compression test far exceeds the resistence limit, longitudinal cracks appear due to the expansion of the specimens.

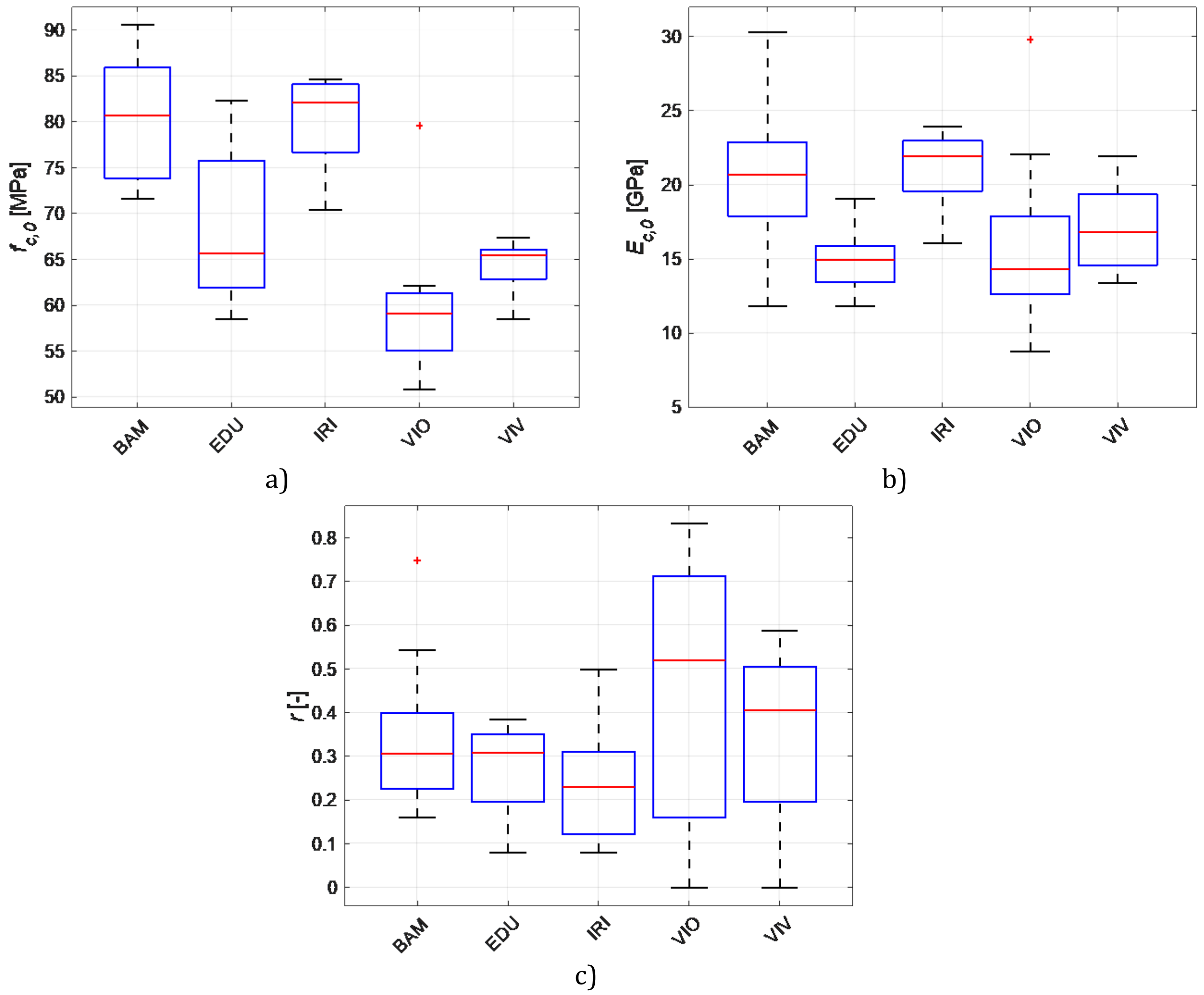


Figure 6. Compression test: (a) strength, (b) Young modulus, (c) Poisson ratio for each species considering all the specimens.

Figure 7. Compression test: failure mode.

2.3.3 Tension test parallel to the fibers

The diagram depicted in Figure 8 shows the longitudinal stress versus the longitudinal strains for BAM species.
In some cases a linear elastic brittle behaviour is encountered, in some other cases there is a non linear beahviour after the maximum stress due to the successive failure of fibers as observed by Amada [Amada, 2001]. The different behaviour is related to different failure modes reported in the following.

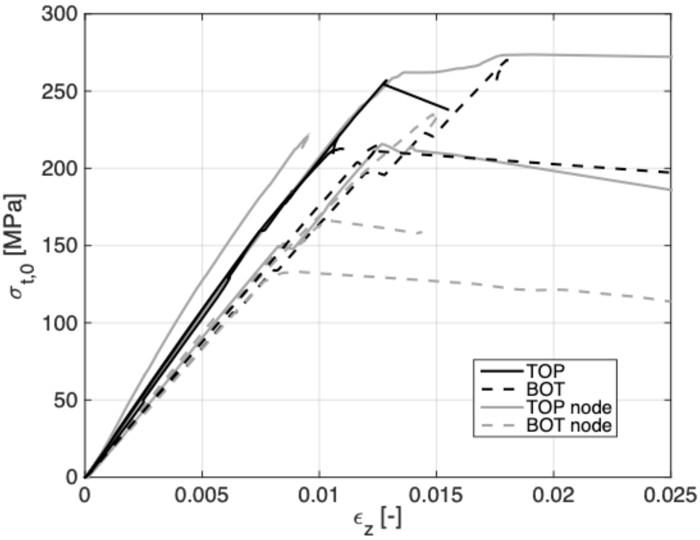


Figure 8. Tension test: examples stress versus longitudinal strain for Bambusoides species.

In Table 3 the mean value and the standard deviation of strength, Young modulus and the relative water content is collected, in Figure 9 the related box plot is depicted.
A variance analysis shows that there are significative differences between BAM and IRI show significative differences with VIO.
Regarding the Young modulus, the variance analysis shows that all the species behave similarly.

Species	$f_{t,0}$ **[MPa]**		$E_{t,0}$ **[GPa]**		w **[-]**	
	Mean	*St.Dev*	*Mean*	*St.Dev*	*Mean*	*St.Dev*
BAM	220.28	41.91	21.80	2.60	9.59	0.78
EDU	193.51	42.73	15.19	2.92	9.09	0.30
IRI	229.38	34.92	18.22	3.12	9.11	0.39
VIO	148.91	31.40	18.17	4.63	9.04	0.23
VIV	188.84	37.62	14.90	4.75	8.94	1.5

Table 3. Tension test: mean values for each species considering all the tested specimens.

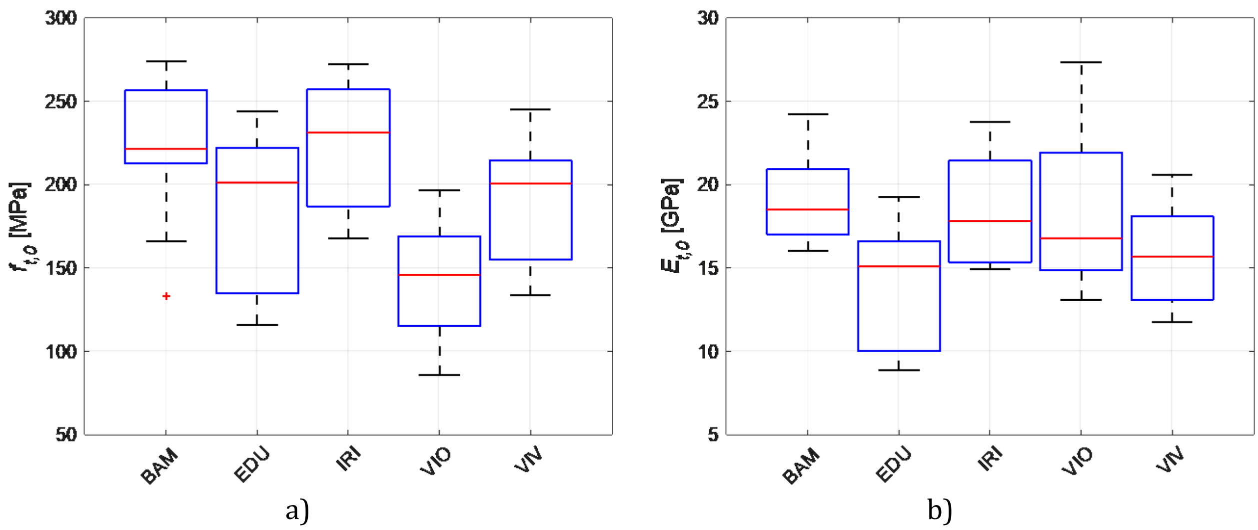
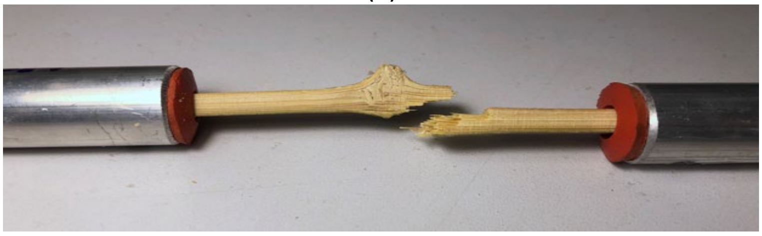


Figure 9. Tension test box plots: (a) strength, (b) Young modulus.

The failure of specimens in tension test can be divided into two groups. The first group experiences a sort of delamination (20 times) (Figure 10a), while a second group experiences a localized fracture (32 times) (Figure 10b). In some cases a failure of the bond between resin and metal pipe occurs (8 times) (Figure 10c). The data of the tests in which this latter failure is encountered, are not considered.

(a)



(b)

(c)

Figure 10. Tension test: failure modes: (a) delamination of the fibers, (b) localized fracture, (c) bonding failure.

2.3.4 Influence of the position of the sample in the culm

The values of compression and tension strength separated for specimens in different positions of the culm, are reported in Figure 11a and Figure 11b. It can be noted that in the upper specimens the tensile and compressive strength are higher in terms of mean values in respect to the specimens extracted from the bottom part of the culm. On the contrary using a variance analysis the differences are not significative except for EDU for compressive strength.
Figure 11c, d and e show respectively, the values of Young modulus in compression and tension and the values of the Poisson ratio in compression. Using a variance analysis also in this cases the differences are not significative except for EDU and BAM for Young modulus in tension.
In Table 4, the ratio between the mean value of strength in tension and compression test for specimen from top and bottom part of culm is reported. The compressive strength decades deeper in respect to the tension strength from the top to the bottom. The species with the higher gap in the tension and compression strength between the top and bottom part of the culm is *Edulis*, which has an evident difference also in geometry between the two parts with a particularly thicker bottom part of the culm in respect to the upper part of culm.

Species	$f_{c,0,TOP}/f_{c,0,BOT}$	$f_{t,0,TOP}/f_{t,0,BOT}$
BAM	1.12	1.11
EDU	1.43	1.17
IRI	1.14	1.09
VIV	1.36	1.10
VIO	1.32	1.07

Table 4. Ratio between mean strength in case of specimen from the bottom part of the culm and from the top part of the culm.

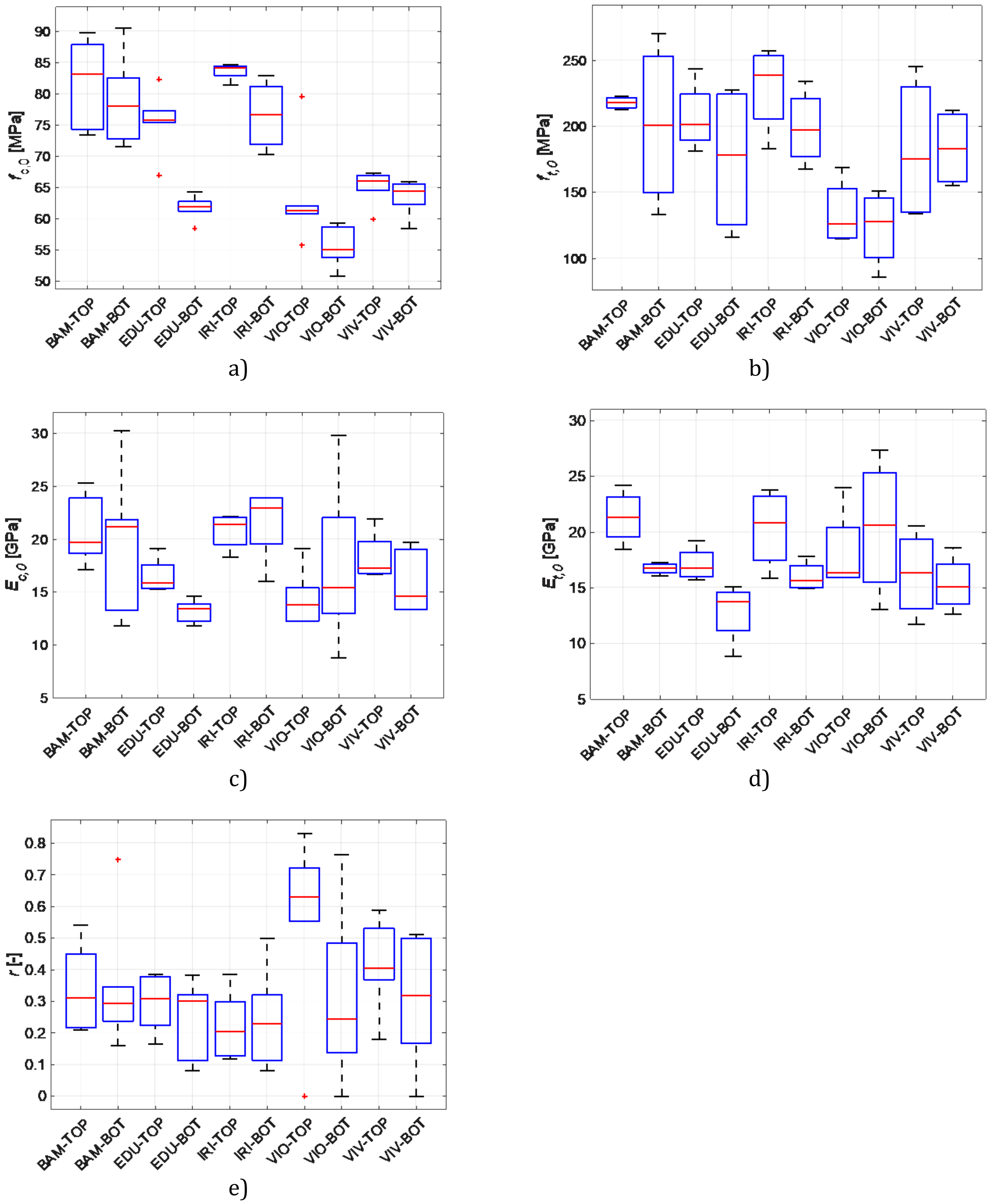


Figure 11. Influence of the position of the culm: (a) compression strength, (b) tension strength, (c) Young modulus, (d) Young tensile modulus and (e) Poisson ratio for all the specimens of each species.

2.3.5 Influence of the presence of the nodes

The presence of node lowers the tension strength in terms of mean values (Figure 12b) while it seems to not significantly influence the other values (Figure 12 a c and d).
Significative differences highlighted by variance analysis van be noted only for tension strength for EDU VIO and VIV.
In Table 5 the ratio between the strength in tension and compression test for specimen with and without node is reported.

Species	$f_{c,0,Internode} / f_{c,0,Node}$	$f_{t,0,Internode} / f_{t,0,Node}$
BAM	0.96	1.12
EDU	0.98	1.47
IRI	1.00	1.14
VIV	1.01	1.36
VIO	1.09	1.32

Table 5. Ratio between mean strength in case of specimen with and without node for compression and tension tests.

2.3.6 Mechanical characteristics versus density

Correlation coefficients between density and the mechanical characteristics as strength, Young modulus and Poisson ratio are reported in Table 6. It can be noted that compression and tension strength show a good correlation with density, while Young modulus and Poisson ratio are not correlated. The regression line between strength and density is shown in Figure 13.

Tension test		**Compression test**		
$f_{t,0}$	$E_{t,0}$	$f_{c,0}$	$E_{c,0}$	r
0.42	0.07	0.73	0.06	-0.17

Table 6. Correlation coefficients between density and the mechanical characteristics as strength, Young modulus and Poisson ratio.

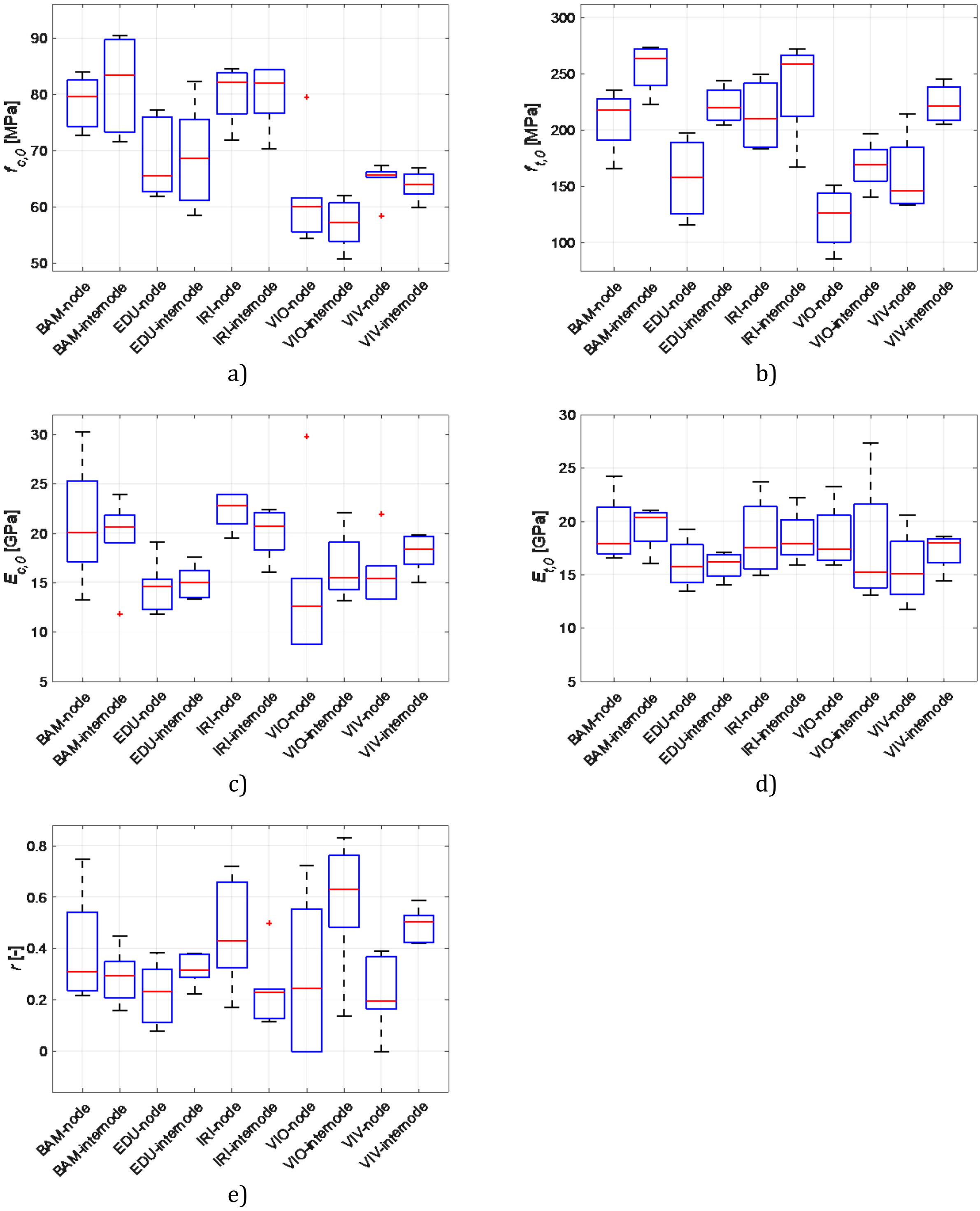
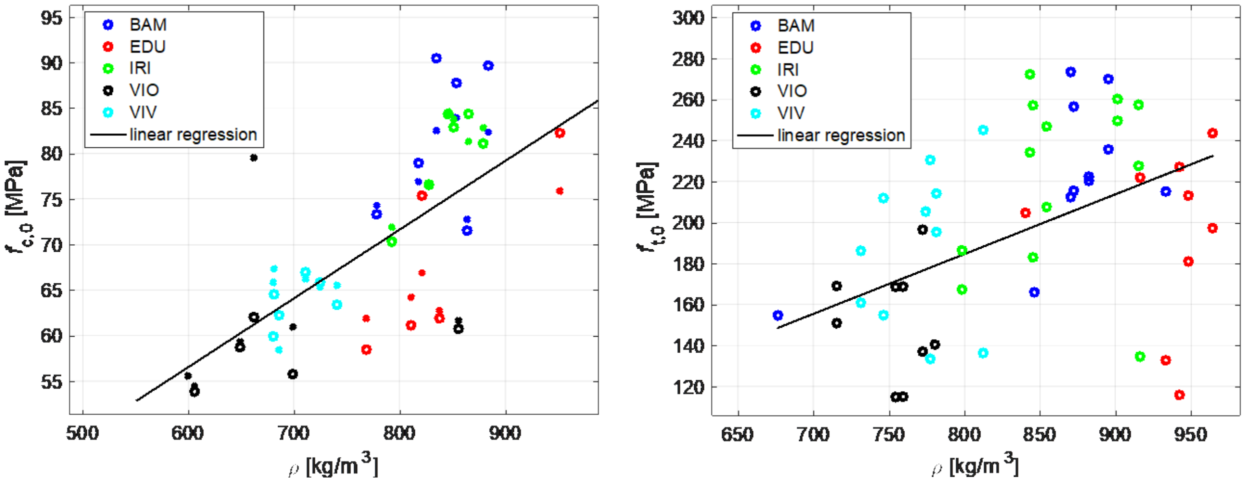


Figure 12. Influence of the node: (a) compression strength, (b) tension strength, (c) Young modulus, (d) Young tensile modulus and (e) Poisson ratio and for all the specimens of each species.



a) b)

Figure 13. (a) Compression strength versus density and (b) tensile strength versus density.

3. Discussion on tension test methodology

In this section we want to deal with tensile test procedure. The main innovation introduced by ISO 22157:2019 in tensile test (in direction of the fiber) is a rectangular cross section specimen "with breadth equal to the culm wall thickness and width equal to one-half the culm wall thickness or less".

This innovation leads to a great simplification of the practical realization of the specimens (with a splitter). The stick required by the norm is incomparably simpler, rapid and, above all, more reliable than the dog bone specimen traditionally used. It leads also to a great advantage because the splitting process does not artificially break the natural path of the fibers.

Further, the configuration allows the jaw to grip equally well the lignin core and the cortical layer. When an appropriate grip system is employed, the better-distributed state of stress at the jaws arrangement makes the interposition of a softwood tab at the ends of the specimen (suggested by ISO 22157:2019, §11.3) essentially useless, as can be seen in the next section.

The small size of the suggested section makes hard to use mini or micro strain-gauge but facilitates mounting a mechanical extensometer (e.g. HBM DD1).

On the contrary the choice of a thin cross section in the circumferential direction make often difficult the splitting of the specimen with a node (ISO 22157:2019 §12.2). In some species, having a relatively small diameter, the sample may be very irregular: the cross-section changes longitudinally and diverges from the rectangular shape (becoming trapezoidal, rhombic or quasi-triangular); the sample may result in bent or twisted.

The last occurrence suggests the inappropriateness of the prescription (§12.1) for which "the grips should also be restrained from rotation about both principal axes of the specimen". Mounting a distort specimen by forcing its natural geometry may alter its response. On the contrary, a mechanical device capable of adaptation avoids the problem (similarly to the spherical bearing surface arrangement provided in the compression test machine "to ensure that the load is concentrically applied", ISO §10.1).

Furthermore, in order to obtain a meaningful experimental tensile strength for the bamboo, the cross-section of the ISO specimen should be *trapezoidal*, namely obtained with splitting planes passing through the ideal axis of the culm. A simple geometrical calculus shows that the over-estimation of the area of a rectangular ISO sample with respect to the trapezoidal correct shape,

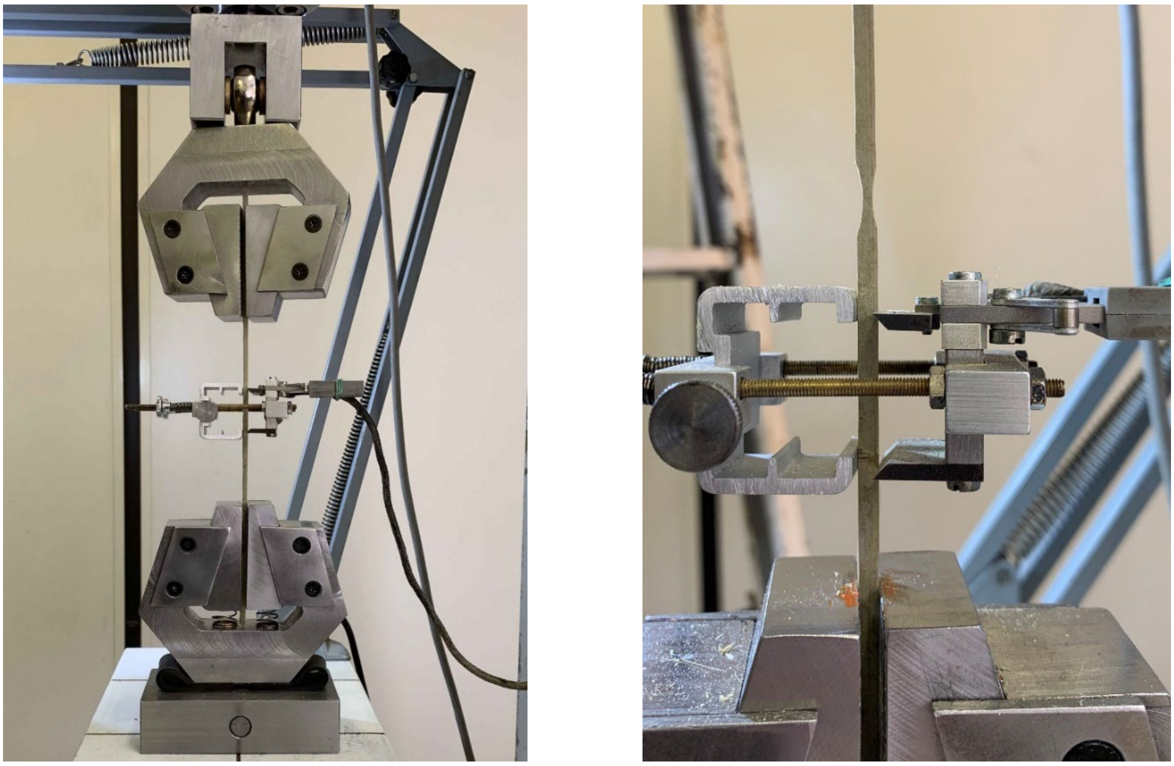
$$\frac{\Delta A}{A_{rect}} \sim \frac{\frac{\delta}{D}}{1-\frac{\delta}{D}}$$

is equal to 5%, 8% and 11% when t/D = 0.05, 0.75, 0.10, respectively.
In the experimental test reported below, the cross-section is trapezoidal and, therefore, its longer and the shorter base are measured, accordingly. No particular problem occurs due to the resulting small non-complanarity at the jaws.

3.1 Alternative set up for tension test

To overcome the difficulties a new procedure for the tensile test is proposed.
An experimental rig has been specifically designed to mitigate the effects of the crushing of the specimen at the jaws (leading almost invariably to a premature collapse). The designed grip system shown in Figure 14a has two original characteristics:

1. the slope of the wedge (3/10) is well greater than in the common uniaxial testing machine, with the aim to distribute the transversal force, compressing the weak part of the material;
2. universal spherical joints connect both the grip system to the fixed frame (load cell and base support, respectively). This arrangement allows the adaptation of non-perfect specimens during the test, either bent or twisted.



a) b)

Figure 14. (a) Experimental rig and (b) a specimen with reduced cross-section.

The aim of this part of the experimental investigation is the appraisal of the innovation introduced in tensile test protocol. For this purpose, a minimal protocol is adopted for each of the 5 species:

- the specimens are obtained *from the same part of the culm* (top), through adjacent simple splits (internode: length ~ 250 mm; with a node: ~300 mm);
- the width is almost one-half of the wall thickness;

- 18 specimens are tested, discarding the most distorted samples: 6 Internode, 6 with a Node, 6 with the Reduced cross-section, as described below, Figure 14b;
- the strain-force time history is registered by an HBM DD1 estensometer and HBM 10kN load cell; the time to failure always exceeds 300 s;
- the specimen is in direct contact with the jaws, without interposition of soft material.

To investigate the possible negative influence of the jaws grip system on the tension strength, and to get a *well-defined and controlled* cross-section, the tests were additionally performed with specimen with a *reduced cross-section in* the middle of an internode sample.
The reduction of area is carried out on the *lateral* sides of the strip, so that the external and internal surfaces of the culm are not disturbed. Therefore, the functionally graded nature of the sample remains unaltered and no corrective factor need to introduce on the strength results.
The width of the specimen is reduced by abrasion with a half-round file, following a template to guaranty a symmetric manufacturing (Figure 14b). The operation is very simple, rapid and repeatable. Since the measurement of the *minimal* cross-section area is now very reliable (with respect to the great variability of the nominal area along an ISO sample), as well as the placement of the critical cross-section, it is expected to reach greater values for strength with reduction of the dispersion.

3.2 Results, Comparison and evaluation of the new procedure

The experimental results obtained with the proposed set up with and without nodes (named respectively 'ISO' and 'ISO-node') and the results obtained for specimen with reduced cross section without nodes (named 'reduced') are synthetically presented in the following graphs in term of strength (Figure 15) and Young modulus (Figure 16) for all the species.

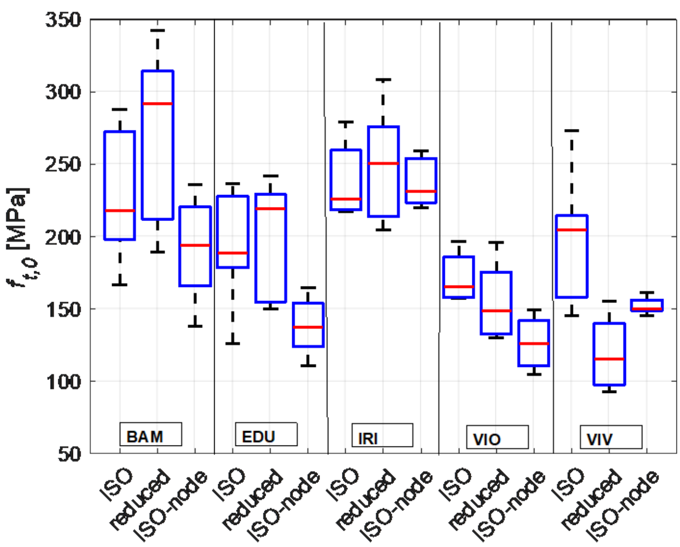


Figure 15. Box plot for strength of the five species.

The examination of the results of the two groups of specimens, allows stating that the ISO specimens give results comparable in terms of ariance analysis with those obtained using the set up described in the first part of the paper (named 'standard'), even though, in the present study, different criteria are used to select the specimens. In particular, Figure 17 shows the mean and the coefficient of variation of the strength and of the Young modulus for all the species.

Species	$f_{t,0}$ [GPa]					
	ISO		**Reduced**		***ISO-node***	
	Mean	*St.Dev*	*Mean*	*St.Dev*	*Mean*	*St.Dev*
BAM	232.31	46.01	288.73	53.10	191.61	35.64
EDU	193.50	38.13	205.45	36.95	138.75	19.06
IRI	243.29	25.11	257.79	35.39	237.83	16.38
VIO	173.61	16.53	159.44	24.97	127.49	16.20
VIV	207.65	40.99	123.73	23.23	152.01	5.79

Table 7. Tension test: mean values and standard deviation of the strength for each species considering all the tested specimens in the three different set up.

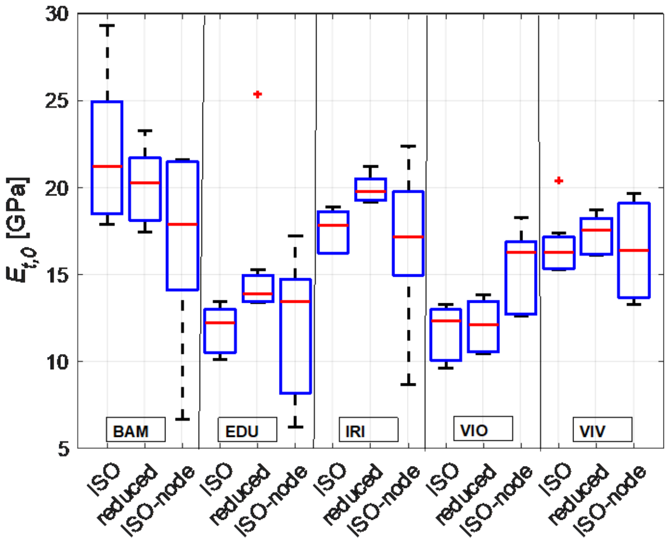


Figure 16. Box plot for Young tensile modulus of the five species.

Species	$E_{t,0}$ [GPa]					
	ISO		**Reduced**		***ISO-node***	
	Mean	*St.Dev*	*Mean*	*St.Dev*	*Mean*	*St.Dev*
BAM	23.03	4.07	20.61	1.99	18.64	8.05
EDU	12.20	1.19	15.93	4.67	12.22	4.16
IRI	17.74	1.17	20.11	0.75	16.60	4.43
VIO	12.05	1.36	12.29	1.43	15.06	2.64
VIV	16.87	1.89	17.45	1.08	20.42	10.22

Table 8. Tension test: mean values and standard deviation of the Young modulus for each species considering all the tested specimens in the three different set up.

For ISO specimen, the value of the strength and Young modulus is often less disperse as shown in Figure 17 by the relative standard-deviation (namely standard-deviation/mean).
It is very interesting to emphasize the failure modes encountered using this testing procedure:

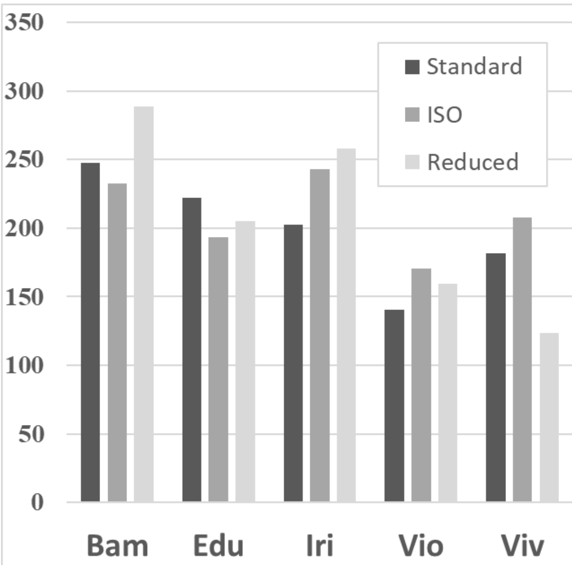
- a distinct de-fibering in the middle zone (Figure 18b);

- delamination of the cortical layer which propagates along the entire specimen (Figure 18, specimen #2).

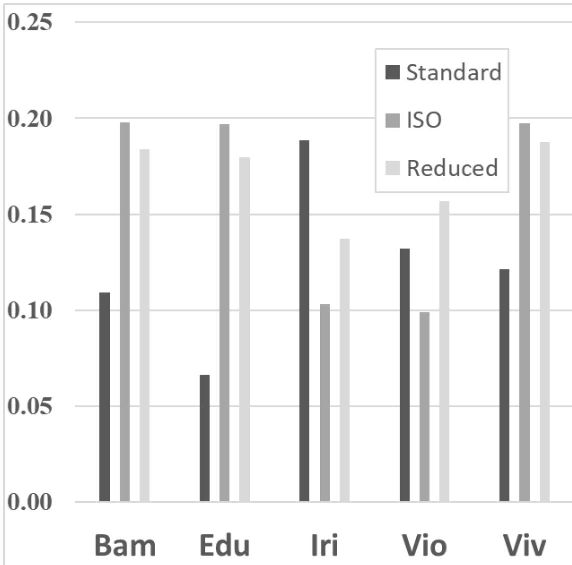
Both modes highlight the great importance to have a sufficient strength in *radial direction* in order to attain a good *tensile* behavior. As a consequence, it seems important to devise a systematic experimental investigation about of the *transversal shear strength*, a parameter appearing inessential, at first sight, in bamboo culms employed for members in tension.
It is worthy of mention a brief comment about the response shown in Figure 19b, of an inter-node sample (BAM N5) affected by a natural knee (Figure 19a), for the possible consequences in structural applications of the culms. In a first phase, the sample responds as two in-series beams, slightly misaligned under traction (smaller stiffness). The increasing tension changes the geometry towards the configuration of two aligned straight beam, whose stiffness (E) is therefore comparable with that of the other samples

Conclusions

The paper presents the results of an experimental study for the mechanical characterization of five species of Italian bamboo . All the species were cultivated in the norther part of Italy. The tested culms have external diameters from 51.13 mm (*VIO*) to 79.43 mm (*VIV*). All the tested species present rather thin culms, from 4.53 mm (*VIO*) to 7.25 mm (*EDU*).



a)



b)

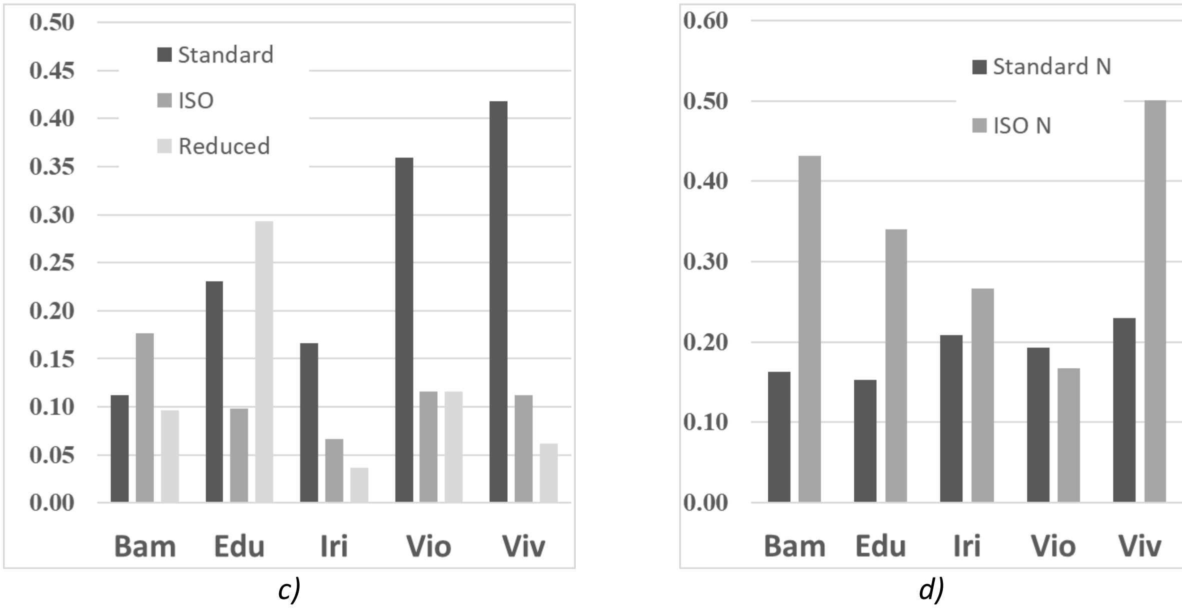
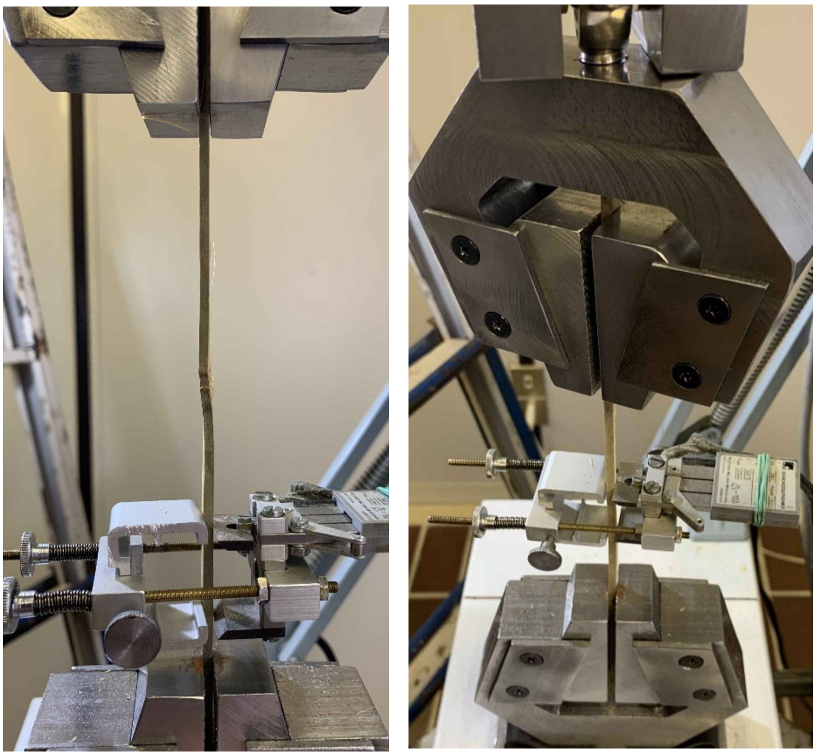


Figure 17 - Comparison of the tensile tests: *a)* Strength values [MPa]; *b)* Strength: Coefficient of variation; *c)-d*) Young modulus: Coefficient of variation.

Figure 18. Two typical failure mode: (a) a defibring in the middle zone zoomed in (b) and a delamination of the cortical layer, in an internode (c) and with Node sample (d).



(a) (b)

Figure 19. (a) Specimen tested with natural “knee” which leads to (b) a natural twist to the anchorage of the press machine.

The main results from **compression tests** are:

- compression strength ranges from a mean value around 60MPa (*VIO*) to the about 80MPa (*BAM* and *IRI*): half of the specimens have been made with nodes and half without; half from the upper part (TOP) and half from the bottom part of the culm (BOT);
- Young modulus ranges from 14.04 MPa (*EDU*) to 20.34 MPa (*BAM*) and 21.89 MPa (*IRI*);
- Poisson ratio, namely the circumferential strain over the longitudinal compressive strain, goes from 0.27 (*EDU*) to 0.47 (*VIO*).

The main results for **tension tests** are:

- tension strength ranges from a mean value of 150 MPa (*VIO*) to 220 MPa (*BAM*) and 230MPa (*IRI*);
- Young modulus ranges from 21.8 MPa (*BAM*) to 14.90 MPa (*VIV*).

The influence of the node and of the position in the culm has been investigated.
The density is quite comparable for *BAM*, *EDU* and *IRI* (860 to 900 kg/m^3), while lower values have been found for *VIO* and *VIV.*
Both tensile and compressive strength are positively correlated with density, whilst no correlation has been found between density and Young modulus or Poisson coefficient ratio.

The second part of the paper discusses critically some aspects of the methodology proposed in recent version of ISO 22157:2019 for tensile tests and describe the appropriate modifications of the experimental set up to be able to perform tension tests also on thin bamboo like the Italian one.
In the paper tests with three different set up are proposed:

- specimen with the extremities buried in a pipe filled by resin;
- specimen with the ISO geometry without soft wood reinforcement at the extremities;
- specimen with a reduced cross-section in the middle of the specimen.

In conclusion, the ISO prescriptions about the tensile tests appear to be a significant and reliable improvement for the mechanical characterization of bamboo culms in the direction of the longitudinal fibers but performing the test as suggested is rather difficult without appropriate experimental rig.
All the three set up proposed are suitable for thin bamboo and present comparable results.
The experimental investigation shows that several autochthone Italian bamboo species have excellent mechanical performance so that they can be adopted as a renewable and sustainable structural material.

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