COMPRESSIVE STRENGTH AND MODULUS OF ELASTICITY PARALLEL TO CULM AXIS OF GUADUA BAMBOO (G. ANGUSTIFOLIA) – EFFECT OF SPECIMEN ASPECT AND SLENDERNESS RATIOS, NODES, DENSITY AND PRESERVATION TREATMENT

FESTIGKEIT UND ELASTIZITÄTSMODUL PARALLEL ZUR STABACHSE VON GUADUA BAMBUS (G. ANGUSTIFOLIA) – EINFLUSS VON PRÜFKÖRPERSEITENVERHÄLTNIS UND SCHLANKHEITSGRAD, NODIEN, ROHDICHTE UND DAUERHAFTIGKEITSBEHANDLUNG

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SUMMARY

The paper reports on compressive strength and modulus of elasticity (MOE) in compression parallel to culm axis of bamboo species Guadua angustifolia of Columbian origin. The investigations were performed in conjunction with two renowned building projects being the Columbian ZERI Pavilion at the Hannover Expo in 2000 and the DIHAD Pavilion presently designed by Nickl & Partner Architects and Werner Sobek Engineers. The test specimens were cut from material shipments of 50 culms (ZERI) with different outer diameters D (76 mm and 134 mm) and wall thicknesses δ (9 mm to 14.5 mm) and 60 culms (DIHAD) with cross-sectional dimensions of D = 91…143 mm and δ = 9…19 mm. At time of the ZERI investigations no internationally agreed bamboo test procedures existed whereas the DIHAD tests were performed in accordance with a meanwhile available bamboo test standard ISO 22157.

The results of both test series revealed an excellent agreement enabling a consistent proposal of characteristic 5% quantile and mean values for compressive strength and MOE, $f_{c,0,k}$ and $E_{c,0,mean}$, of 40 N/mm² and 18500 N/mm², respec-

tively. The specified characteristic material shape properties are bound to a characteristic density of $\rho_{12,k} = 600$ kg/m³ and cross-sectional dimensions of $D \geq 75$ mm and $\delta \geq 8$ mm.

The comparative evaluation of both time wise two decades distanced test series showed that nodes consistently decrease the compressive strength D- and δ- dependent by maximally 10%. Compressive strength yet no MOE decreases with increasing cross-section area A. With regard to a more mechanics sensible test procedure the ISO 22157 provisions should be altered. Instead of specimens' aspect ratio $l/D \leq 1$ which does not account for culm wall thickness a buckling slenderness ratio in the range of 3 – 8 and 2.4 -12.4 for the sample means and individual specimens, respectively, should be specified. Further, it is noteworthy to mention that a specific Japanese smoke treatment for durability enhancement showed no noticeable impact on compression strength and MOE. This seems to apply for a sodium pentaborate treatment, too.

ZUSAMMENFASSUNG

Der Beitrag berichtet über die Druckfestigkeit und den Druck-Elastizitätsmodul (MOE) parallel zur Rohrachse der Bambusart Guadua Angustifolia kolumbianischer Herkunft. Die durchgeführten Untersuchungen stehen im Zusammenhang mit zwei renommierten Bauvorhaben, dem kolumbianischen ZERI Pavilion bei der Expo Hannover 2000 und dem in der Auslegung befindlichen DIHAD Pavilion (Nickl & Partner Architekten, Werner Sobek Ingenieure). Die Prüfkörper wurden aus Materiallieferungen entnommen, die im Falle des ZERI Pavilions 50 Stäbe mit verschiedenen Außendurchmessern (D = 76…134 mm) und Wandstärken (δ = 9…14.5 mm) und bei dem DIHAD Projekt 60 Stäbe mit Querschnittabmessungen D = 91…143 mm und δ = 9…19 mm umfassten. Zum Zeitpunkt der ZERI Untersuchungen existierten keine international akzeptierten Versuchsvorgaben, wohingegen die DIHAD Versuche in Übereinstimmung mit der zwischenzeitlich eingeführten Bambus-Prüfnorm ISO 22157 durchgeführt wurden.

Die Ergebnisse beider Versuchsreihen zeigten sehr gute Übereinstimmungen, die konsistente Vorschläge für einen charakteristischen 5% Quantil-Druckfestigkeitswert $f_{c,0,k}$ und ein Elastizitätsmittelwert $E_{c,0,mean}$ von 40 N/mm² bzw. 18500 N/mm² ermöglichen. Die genannten charakteristischen Material- / Struktureigenschaften sind gebunden an eine charakteristische Rohdichte von $\rho_{12,k} = 600$ kg/m³ und Querschnittsabmessungen von $D \geq 75$ mm und $\delta \geq 8$ mm.

Die vergleichende Auswertung beider Versuchsreihen ergab übereinstimmend, dass Nodien die Druckfestigkeit, D- und δ-abhängig, um maximal 10% reduzieren. Die Druckfestigkeit, jedoch nicht der Elastizitätsmodul, nimmt mit zunehmender Querschnittfläche A ab. Mit Bezug auf eine mechanisch sinnvollere Versuchsdurchführung sollten die ISO 22157 Vorgaben für die Prüfkörpergeometrie, die ausschließlich die Länge l und den Außendurchmesser D berücksichtigt, geändert werden. Anstelle eines Prüfkörper-Seitenverhältnisses $l/D \leq 1$, das die Wanddicke nicht berücksichtigt, sollte ein Beul-Schlankheitsverhältnis im Bereich von 3 – 8 bzw. von 2.4 – 12.4 für den Mittelwert und die Einzelwerte des Prüfkörperkollektivs gefordert werden.

Es ist des Weiteren hervorzuheben, dass eine spezifische japanische Räucherbehandlung der Bambusstäbe zur Dauerhaftigkeitserhöhung keine nachweislichen Auswirkungen auf die Druckfestigkeit und den Elastizitätsmodul bewirkt. Dies scheint auch für eine Natrium-Pentaborat-Behandlung zuzutreffen.

1. INTRODUCTION

Bamboos represent one of the most fascinating renewable natural materials. It recovers significantly more carbon dioxide as wood per kilogram mass during its lifecycle hence shows a much higher green house effect than trees. Bamboos belong to the fastest growing plants of the world with a growth rate up to about 90 cm culm length per day. Bamboo culms are hollow cylinders with diameters, wall thicknesses and heights ranging from 10 to 250 mm, 2 to 35 mm and 1 to 40 m, respectively. The culm consists of internode sections being undisturbed hollow cylinder segments and nodes confining the internode lengths by transverse diaphragms which serve mechanically for radial strength and stiffness. Although this paper addresses exclusively some mechanical material aspects of a specific bamboo species it should be pointed at the fact that bamboos not only represent a structural material but are a most versatile generic source for tissues, pulp and paper, nutrition and medicines. Regarding structural use, many bamboo species are excelled by outstanding material properties and hence represent one of the oldest building materials of the world especially in the tropics.

However, similar as in case of timber, the mechanical and durability properties of bamboo vary considerably between genera and species and analogous to trees the properties are very sensitive to soil and climate conditions within species. Unlike timber so far no internationally agreed bamboo grading and classification system similar as for instance for timber by European standards EN 14081 [1], EN 384 [3], EN 338 [4] and EN 1912 [5] exists what states a significant hindrance for border overarching reliable use of this material.

The structurally most import genera comprise Bambusa (150 species), Dendrocalamus (60 species), Gigantochloa (70 species), Phyllostachys (50 species), all natives to south-east Asia, India and China, and Guadua being the most important bamboo genus in Middle and South America. Guadua comprises about 30 species of which Guadua angustifolia (G. a.), focused in this contribution, is by far the most important species essentially grown and harvested in Columbia, Ecuador and Venezuela. Presently about 50 000 ha of G. a. are cultivated in Columbia. Guadua a. grows by about 10 cm per day within the first six months and reaches a height of about 20 to 30 m. The average culm diameter is in the range of about 11 cm and culm wall thickness varies from about 30 mm to less than 10 mm at the base and top, respectively.

MPA University of Stuttgart has worked in the last two decades within several material testing, construction and design tasks with this material. Major contributions to so-called decisions in the single case of German building authorities were made i.a. within the erection and design of the ZERI-Pavilion at the EXPO 2000 [1] in Hannover, for the Chinese Pavilion at the “Festival of Vision Hongkong – Berlin” in Berlin 2000 and more recently within a private sector commissioning for the DIHAD Pavilion designed by Nickl and Partner Architects and Sobek Engineers.

This paper represents the first of a series of contributions related to material properties and relevant tests for bamboo material with a special focus on the species Guadua Angustifolia. The article covers the axial compressive strength and modulus of elasticity (MOE) parallel to the longitudinal culm axis.

2. BRIEF LITERATURE REVIEW

Introductory to the brief literature review it has to be recalled that the material “bamboo” shows an extreme diversity in growth and mechanical properties. Hence there is no unique “compressive strength” of bamboo alike there is no such strength for timbers. As stated above the combined efforts of science and industry have managed in North America and Europe to classify structural timbers in a wood species overarching approach by assignments to strength classes. In Europe this is followed up by a consistent sampling, testing, evaluation and strength class assignment procedure outlined introductory. In case of bamboos such an approach is missing and most published results refer exclusively to individual species and rarely contain comparisons with species of other genera. Literature addresses in very confined manner bamboos grown in South East Asia especially Indonesia, China and India and in South / Middle America. Finally, it has to be stated that the lack of an international bamboo test standard up to the year 2019, now ISO 22157 [7], was detrimental as very different test and evaluation procedures, being hardly or not at all comparable, have been used in the past.

One of the first substantial contributions on bamboo strength and stiffness has been published by Atrops in 1969 [8]. The investigations comprised bending, shear and compression of bamboo native to Trinidad, however, unfortunately no genus or species was reported. In the following, regarding [8] and further literature, only aspects dealing with compressive properties parallel to culm and (internode) fiber axis are discussed. The culm segments tested in [8] had very closely matching mean values of outer diameters D and wall thicknesses δ of 77 mm and 7 mm, respectively. All specimens had an aspect ratio $l/D = 4$. Three geometry types a - c were investigated having no node (a), a node close to each loaded end grain face (b) and a node at mid-length (c). Moisture content was 18% and density was ρ_{18}= 730 kg/m³. The moisture content of 18% is below fiber saturation which in case of bamboos is around 22%, so much lower as in case of wood where a range of 28-32% applies.

The compressive strengths of all test series agreed very well. Series a and b showed closely matching average values of 40.5 N/mm² whereas series c gave a somewhat (7%) increased strength of 43.3 N/mm². The reason for the higher value in series c was attributed by Atrops to the radial reinforcement of the mid-length located node diaphragm. Complementary to shape strength also the clear wall strength was measured at specimens with dimensions (wall thickness x width x length) of 7 mm x 16 mm x 25 mm resulting in a 1.5 times higher mean strength of 62.1 N/mm².

Janssen (1981) presents an overview on then literature known compressive strength tests with respective specimen dimensions and highlights a vast strength spread in the range of 35 N/mm² up to 85 N/mm² whereby uncertainties on moisture contents exist [9]. Own investigations by Janssen on bamboo species Bambusa Blumeana from the Phillipines were performed with specimens cut from three culms with diameters of 70 – 90 mm and culm wall thicknesses of 5 – 9 mm.

The specimen lengths were 50 mm, 100 mm and 200 mm. The results obtained for specimens with and without nodes for a moisture content of 12% varied from minimally 61 N/mm² to maximally 104 N/mm². The mean compressive strength $f_{c,0,mean,12}$ evolved as 81 N/mm². Specimens cut from the top of the culm showed in average 15% higher compressive strength values ($\bar{x}$ = 85 N/mm²) than specimens taken from the culm base ($\bar{x}$ = 74 N/mm²). The effect of nodes was found being insignificant.

Concluding this brief introduction into compression specimen sizes and result spreads the research of Ghavani [10] is regarded. The reason for that reference choice is that the investigations are related somehow to bamboo species and origin of the reported G. angustifolia tests. In [10] seven different bamboo species belonging to three different genera, being Bambusa, Dendrocalamus and Guadua, all natives to South and Middle America, were investigated.

The bamboos harvested in the state of Rio de Janeiro, Brazil, included three Bambusa species with rather small diameters in the range of 25 – 40 mm at the base and 15 – 30 mm at the top, disregarded hereinafter. Four species, with hereinafter quantitatively discussed results, being Guadua superla, Bambusa vulgaris, B. vulgaris Schard and Dendrocalamus giganteus showed base and top diameters in the range of 60 – 160 mm and 46 – 130 mm, respectively, see Table 1. The culm wall thicknesses (mean values at base and top) varied from 6 – 12 mm. Excluding the fairly light Bambusa vulgaris species with a mean specific density of 650 kg/m³, the densities at base and top varied from 660 – 1000 kg/m³ and 700 – 820 kg/m³, respectively. The compression specimens had a length of two times of the outer diameter D and contained partly nodes at mid-length. The moisture content at testing ranged from 13.9 – 19.5 % and was in average 17.3%.

The compressive strength and stiffness values varied profoundly between species whereby the highest differences were obtained for specimens with a node; here strength ranged from 11.6 N/mm² (B. vulgaris, upper culm part) to 58.8 N/mm² (D. giganteus, base part). Apart from one exception (D. giganteus, base part) $f_{c,0}$ of specimens without a node exceeded the strength of the related specimens of the same species with a node significantly. In case of species G. superla, B. vulgaris Schard and D. giganteus the ratios $f_{c,0,mean,no\ node} / f_{c,0,mean,node}$ ranged from 1.16 to 1.50 with an average of 1.3. In case of B. vulgaris extreme ratios of 2.8 and 3.9 were obtained.

Modulus of elasticity (MOE) $E_{c,0}$ – not measured in the above discussed references ([8], [9]) – was determined by [10] in the range of 2170 to 4560 N/mm^2, see Table 1.

Table 1: Compilation of culm diameters, wall thicknesses, moisture contents, densities, compressive strength and MOE of different tropical Latin American bamboo species

species (color)	**culm section 1)**	**diameter 2)**	**culm wall thickness 3)**	**moisture**	**density**	**compressive strength**		**compressive MOE 4)**	
						with node	**no node**	**with node**	**no node**
		mm	mm	%	kg/m^3	N/mm^2		N/mm^2	
Guadua superba (green)	u	70	6	19	730	35.0	45.0	2830	3550
	l	110	9	18	1000	36.4	50.6	2460	3120
Bambusa vulgaris (yellow with green stripes)	u	65	5	16	620	11.6	32.0	2030	2460
	l	74	10	16	680	13.0	50.2	2170	2490
Bambusa vulguris Schard (green)	u	55	7	16	700	42.0	59.0	2800	3670
	m	65	9.5	17	780	39.5	46.0	2360	3190
	l	100	10	18	660	37.5	53.0	2600	2860
Dendrocalamus giganteus (dark green)	u	70	7	14	820	32.6	49.0	2450	3080
	um	95	8	17	900	37.5	50.0	4100	4580
	m	110	9	19	980	32.9	47.5	4010	4460
	lm	125	10	19	870	33.0	41.5	3750	4560
	l	145	12	20	860	58.8	39.7	3570	3410

1) u = upper, l = lower = base, m = middle, um = upper middle, lm = lower middle
2), 3) averages determined from both sections ends
4) see text for critical assessment of specified values

In all cases with one exception - again D. giganteus, base part - compressive MOE with specimens without node exceeded the value of specimes with a node by factors of 1.1 to 1.35 and in average the ratio $E_{c,0,mean,no\ node} / E_{c,0,mean,node}$ was 1.20. Regarding the specified absolute MOE level it has to be concluded that the values should be wrong, i.e. are much too low. This clear statement is substantiated by much higher yet still too low tensile MOE values in [10] and e.g. by investigations reported here.

The reason for the published unrealistically low MOE values is most probably bound to the use of the total vertical displacement between the loading plates which includes i) additional displacement contribution from gradual settings in the compression equipment and ii) crushing and settings at the loaded specimen ends. These effects are highlighted exemplary in MOE measurements reported below. A true, physically realistic MOE can only bee determined as in case of wood by displacement or strain measurements within the free specimen length with sufficient distance from the loaded ends. This stipulated for solid timber in EN 408 [6] since long and more recently in ISO 22157 [7] for bamboo tests, too. Similar erroneous MOE findings resulting assumingly from the same mistake in displacement measuring are reported in several further bamboo research papers, e.g. in [17] and [18].

3. MATERIAL

The investigated and reported bamboo material (Guadua angustifolia) originates in both cases (ZERI Pavilion and DIHAD Pavilion) from Columbia. The materials were delivered to MPA in 1999 and 2021, respectively. The ZERI bamboo consisted of two delivery shipments 1 and 2 with 20 and 30 culms of different sizes (see below). The ZERI bamboo culms of shipment 1 had a deep brown/black color and a strong smoke smell, resulting from a special smoking treatment according to Japanese preservation provisions in order to increase the natural durability against fungi and insects. Shipment 2 of ZERI consisted of untreated culms. In case of the DIHAD material the culms were preservative treated by immersion in sodium pentaborate.

The DIHAD material was delivered with three groups I-III characterized by different nominal culm diameters and wall thicknesses of I (100 mm and 10 mm), II (130 mm and 12 mm) and III (140 mm and 16 mm), respectively. The lengths of the culms for the compression tests equaled about 10 times the outer diameter D.

Table 2 shows a statistical evaluation of the outer diameter D and the culm wall thickness δ of the compression specimens of the ZERI shipments 1 and 2 and of the specimens from the three culm groups I - III of the DIHAD bamboo. The culm wall thickness δ_{mean} represents the mean value of four measurements per specimen. The first of the ZERI shipment bamboo specimens had a mean diameter and culm wall thickness of $D_{mean,ZERI,1} = 125.5 \pm 13.6$ mm and $\delta_{mean,ZERI,1} = 12.6 \pm 0.7$ mm, respectively. The second shipment consisted of slightly smaller cross-sections with values of $D_{mean,ZERI,2} = 87.7 \pm 14.9$ mm and $\delta_{mean,ZERI,2} = 10.6 \pm 1.9$ mm. Different hereof the three DIHAD groups show very little COVs of 3 - 5% for the mean values of the outer diameter D, because they were somehow graded according to their culm diameter in each group. As can be seen from Table 2, DIHAD groups I and II had similar but slightly bigger cross-section values as the two ZERI shipments. DIHAD group III consisted of a quite big bamboo cross-section of $D_{mean,DIHAD,III} = 134{,}6 \pm 7{,}6$ mm and $\delta_{mean,DIHAD,III} = 16{,}3 \pm 1{,}8$ mm and consequently is not comparable to the ZERI culms in all aspects.

Table 2: Compilation of the culm wall thicknesses δ_{mean} and outer diameters D of the ZERI and DIHAD bamboo compression specimens

		mean $\bar{x}$	**± std.** **s**	**COV** **V**	**minimum** x_{min}	**maximum** x_{max}
		mm	mm	%	mm	mm
ZERI shipment 1	δ_{mean}	12.6	0.7	5.6	11.7	14.5
	D	125.5	13.6	10.8	85.4	134.3
ZERI shipment 2	δ_{mean}	10.6	1.9	18.1	8.8	13.3
	D	87.7	14.9	14.9	76.1	117.7
DIHAD group I	δ_{mean}	11.6	2.1	18.3	8.6	14.6
	D	95.4	2.6	2.8	91.1	99.8
DIHAD group II	δ_{mean}	14.9	2.3	15.5	10.9	19.1
	D	132.2	3.9	3.0	123.3	136.6
DIHAD group III	δ_{mean}	16.3	1.7	10.7	12.1	18.8
	D	134.6	7.4	5.5	115.2	142.5

4. SPECIMENS AND COMPRESSION TEST PROCEDURE

4.1 ZERI bamboo

At the time of the ZERI investigations no relevant European and international test and evaluation standards for bamboo existed. Hence the tests were performed with consideration to EN 408 [1] and a few relevant publications (i.a. [8], [9], [10]). As it was not fully evident from literature to what extent the specimen aspect ratio, the presence of nodes and respective distances to the loaded end grain faces affects the compressive strength and modulus of elasticity (MOE), specimens with significantly different geometries and sizes were tested. The specimen lengths varied from 48 mm to 394 mm, whereby specimens with a centrical node had a minimum length of 100 mm. The aspect ratio of the specimens (length l / outer diameter D) varied from 0.4 to 4.6. The ratio of culm wall thickness δ vs. culm radius $r = D/2$ varied from 3.0 to 5.5.

$$\lambda = l/i \tag{1}$$

with

l total specimen length

i radius of inertia, $i = \sqrt{\frac{A}{4\pi} \cdot \frac{1+(1-\rho)^2}{1-(1-\rho)^2}}$ with $\rho = \left(\frac{D}{2\delta}\right)^{-1}$ (2a,b)

D outer culm diameter

δ culm wall thickness

A area of the culm cross-section,

$$A = \frac{\pi}{4} \cdot [D^2 - (D - 2\delta)^2] = \pi \cdot \delta \cdot (D - \delta) \tag{3}$$

The specimen slenderness ranged from 1.2 to 12.6. The specimens were taken from the culms according to the cutting pattern shown exemplarily in Fig. 1 [15]. The compressive tests were divided in five types consisting of specimens without a node (types A1, A2 and A3) and those with a node at mid-length (types B1 and B2). The specimen lengths are given in Fig. 1.

Modulus of elasticity was measured in the central part of the specimen with absolute gauge lengths of 50 mm to 200 mm. Hereby the gauge length encompassed throughout at least 50% of the total specimen length. Fig. 2 shows a schematic drawing of the compression displacement measurement and Fig. 3 (a) represents the realized test set-up. The displacement was measured at three locations distanced by 120° at the outer periphery of the culm. The compressive load was applied by stiff steel plates resting on spherical hinges, blocked with regard to rotation after 10% of the estimated maximum load. The end planes of the specimens were prepared parallel to each other and perpendicular to the length axis of the specimen.

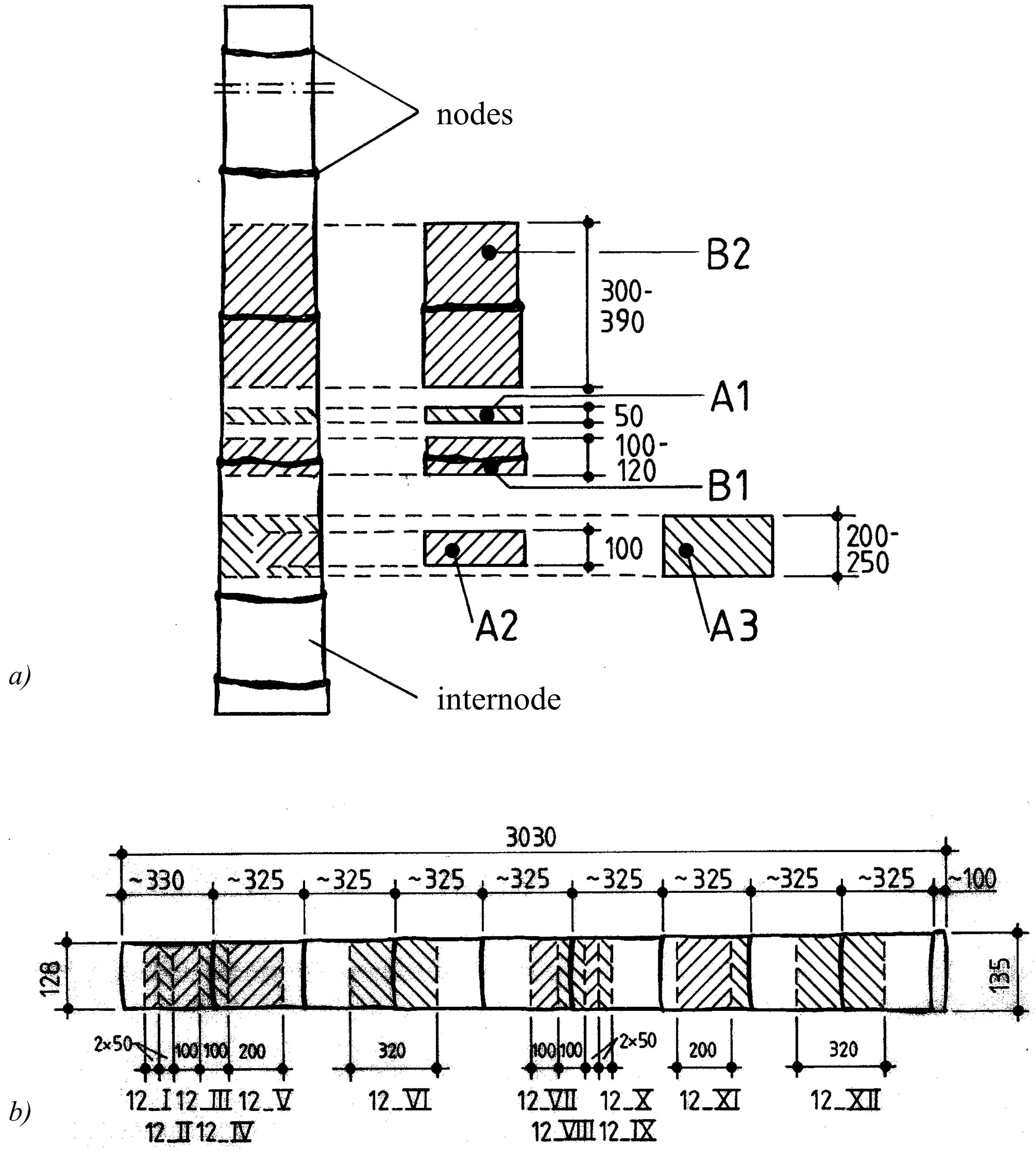


Fig. 1: Cutting pattern for the specimen types A1-A3 (no nodes) and B1, B2 (with a node)
a) principle of cutting scheme and dimensional ranges
b) exemplarily for culm No. 12

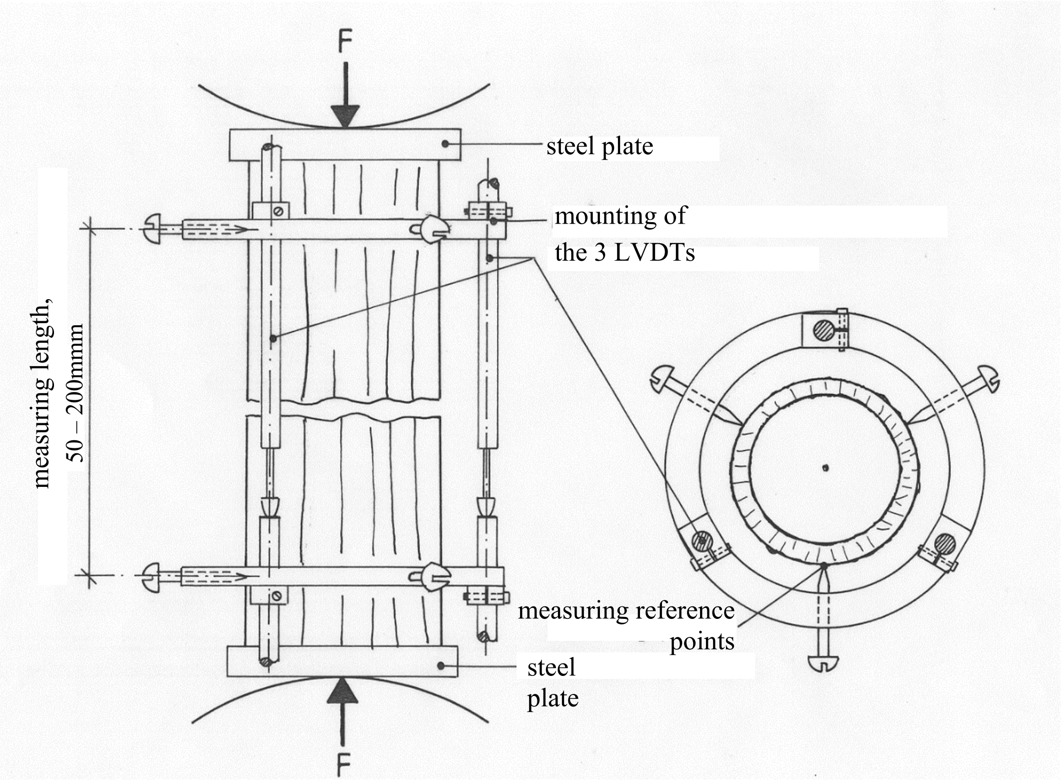


Fig. 2: Schematic drawing of the ZERI bamboo compression test-set up and displacement measurement

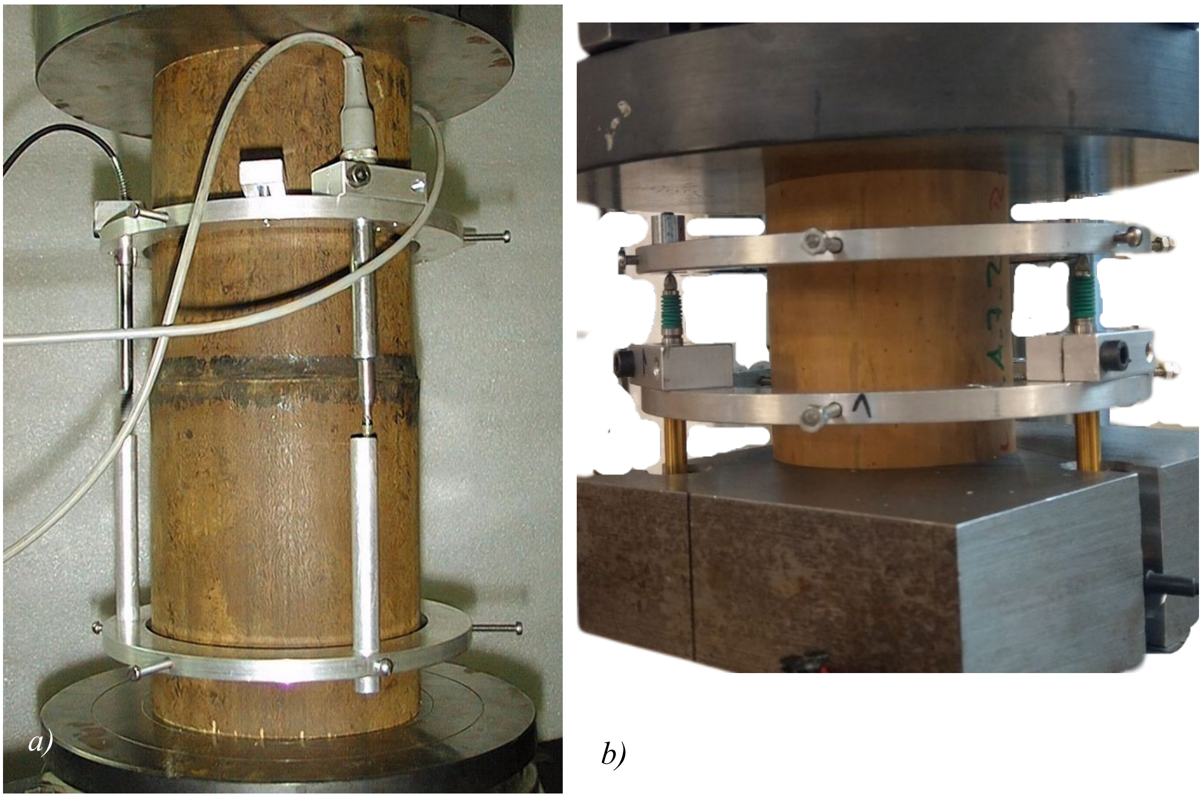


Fig. 3: Pictures of the realized compression test set-ups
a) for a ZERI specimen of type B2, b) for a DIHAD specimen with D = 100 mm

4.2 DIHAD bamboo

The compressive tests were performed in a close follow-up of the international bamboo testing standard ISO 22157:2019 [7], developed in ISO TC165. The standard specifies that the length of the specimen shall be take as

$$\begin{aligned} l &= \min\begin{cases} D \\ 10 \cdot \delta \end{cases} && for\ D > 20\ mm \\ l &= 2D && for\ D \leq 20\ mm. \end{aligned} \qquad (4a,b)$$

Nodes, when present, shall be located approximately at mid-height. The compression tests parallel to the fiber shall be made on specimens, 50% with a node and 50% without. The standard provisions on the specimen length as dependent on either diameter D or culm wall thickness δ (in the given case of D > 20 mm) led to rather constant slenderness ratios of λ_{DIHAD} = 2.6 - 3.7. Thus, the investigated λ-range was much more narrow and towards the lower end as compared to the ZERI tests (there: λ_{ZERI} = 1.2 – 12.6).

The preparation of the end planes is specified [7] in detail with regard to deviations. To measure the compressive modulus of elasticity parallel to fiber $E_{c,0}$, either strain gauges or mechanical / LVDT gauges are permitted whereby minimally two devices have to be placed uniformly at the circumference. Fig. 3 (b) shows the realized test set-up, being in principle analogous to the test-set up of the ZERI bamboo investigations. Different from the ZERI bamboo tests MOE was measured at all specimens.

With regard to application of the compressive force to both loaded end grain faces of the specimen the standard ISO 22157 specifies an intermediate layer consisting of a PTFE sheet with radially oriented steel shims to minimize friction at, and radial restraint of the specimen ends. However, it turned out that the PTFE sheets did not work. Although the intention to minimize friction of the loaded specimen ends is well understood, a proper realization of the proposed method is hard to perform. Using an unreinforced PTFE leads to crushing of the PTFE shim and a steel reinforced PTFE hardly allows sliding. Hence the tests were conducted without an intermediate layer.

The tests were performed as in case of the ZERI bamboo in a heated but non climatized environment in a computer-controlled servo-hydraulic test machine. The displacements of the loading piston and of the LVDTs were continuously recorded and stored in a data acquisition system. The load was applied in stroke control with a constant displacement rate of 0.2 mm/min in order to achieve failure in 300 ± 120 s, equally specified in EN 408 and ISO 22157.

5. TEST EVALUATION AND RESULTS

The evaluation of compressive strength and modulus of elasticity was done in all cases as sensible and stipulated in ISO 22157 according to

$$f_{c,0} = F_{ult}/A, \tag{5}$$

$$E_{c,0} = \frac{F_{60} - F_{20}}{A \cdot (\varepsilon_{60} - \varepsilon_{20})} \tag{6}$$

with

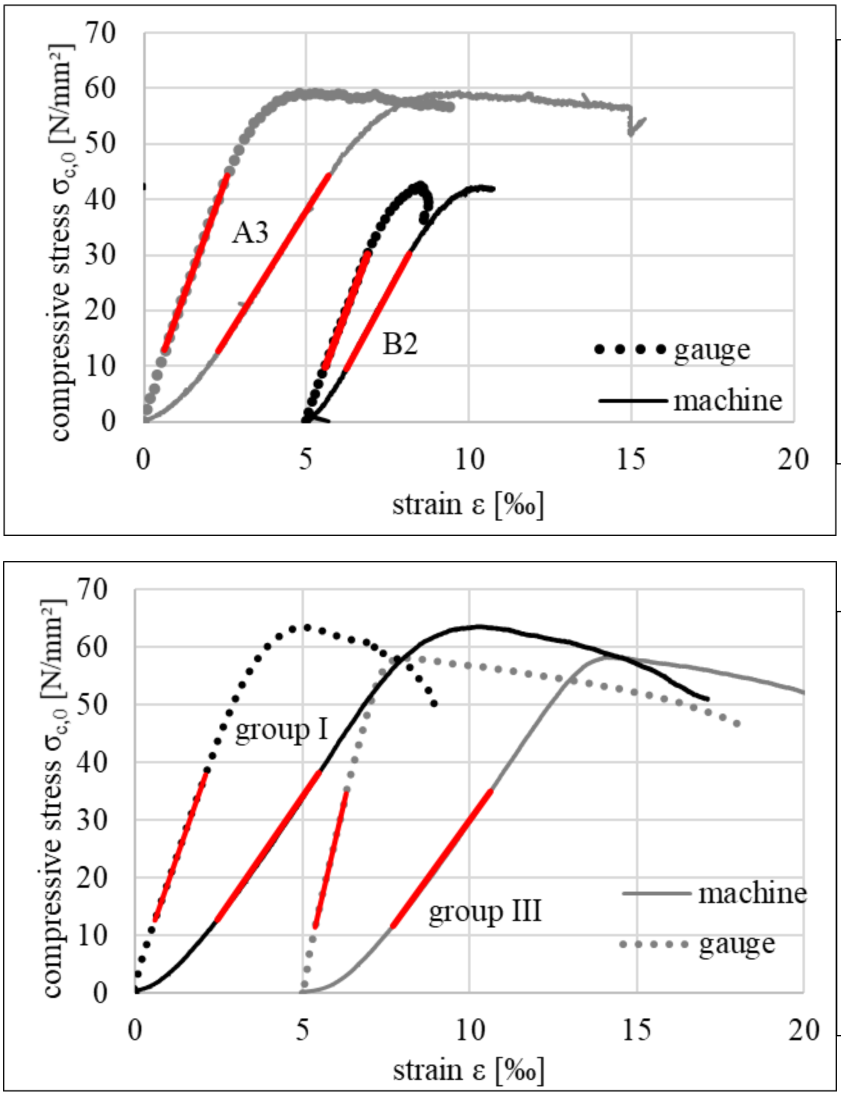
F_{ult}	maximum load at which the specimen failed
A	cross-sectional area defined in Eq. (3)
F_{20}, F_{60}	applied load at 20% and 60% of F_{ult}
$\varepsilon_{20}, \varepsilon_{60}$	mean of the strain gauge readings obtained at 20% and 60% of F_{ult}

5.1 Stress - strain behaviour and fracture modes

Fig. 4 a) and b) show typical stress-strain curves of ZERI and DIHAD specimens which were very similar and can be characterized as follows. Firstly, a linear load displacement behavior is observed until about 80% of the ultimate capacity followed in most cases by progressive non-linear stiffness then ending at almost all specimens in a quasi-plastic slightly softening plateau. The strain at the ultimate stress was reached at most specimens within a range of 0.2 - 0.5%. The plastic behavior in some specimens reached ultimate strains at failure up to 1.5% until a significant load drop was detectable. Visually detectable failure appearances such as compression wrinkles or local buckling of the culm wall occurred throughout at all specimens exclusively in the softening range. In most cases the compression failure has to be characterized as being very good-natured, i.e. without pronounced load drops. At a few specimens a partly / rarely total splitting parallel to fiber could be observed. Then instead of a softening plateau a rather fast load drop occurred (see Fig. 4a, specimen B2).

Regarding the MOE evaluation Fig. 4a and 4b show both, the stress – strain curves derived from i) with the results of the strain gauge measurements and ii) from the recorded piston displacement. The results of the MOE evaluations based on either piston displacement or strain gauge measurement are given on the right side of the respective graphs, where ratios of $E_{c,0,gauge}$ / $E_{c,0,machine}$ of 1.5 to 3 can be observed. This demonstrates, that the demand for a strain gauge or LVDT measurement along the center part of the specimen is indisputable for a proper MOE calculation. This significantly lower $E_{c,0,machine}$ results explain the extremely low MOE values specified in [10], [17] and [18] to some content. A further reason for the low literature values should stem from the higher moisture contents of the specimens in the mentioned literature sources.

a)



specimen type A3:

$E_{c,0,machine}$ = 9 300 N/mm²

$E_{c,0,gauge}$ = 16 500 N/mm²

specimen type B2:

$E_{c,0,machine}$ = 10 700 N/mm²

$E_{c,0,gauge}$ = 15 500 N/mm²

b)

specimen group I:

$E_{c,0,machine}$ = 8 400 N/mm²

$E_{c,0,gauge}$ = 16 600 N/mm²

specimen group III:

$E_{c,0,machine}$ = 8 000 N/mm²

$E_{c,0,gauge}$ = 24 900 N/mm²

Fig. 4: Typical stress-strain curves derived from either LVDT measurement at centre gauge length or from total cross-head displacement
a) for ZERI specimens of types A3 and B2 and b) for DIHAD specimens of groups I and III

5.2 ZERI bamboo

Table 3 gives a condensed compilation of the compressive strength results separately for the different specimen types A1 to B2 and for the entity of the specimens excluding type A1 for a below mentioned reason. As apparent, the very short and stout specimen type A1 with a length of 50 mm and an average slenderness ratio of 1.5 gives a significantly higher compressive strength as compared to all other configurations. This is sensible as the stressed volume shows a much-reduced eccentricity and a higher impact of the radial restraint at the loaded ends. The assessment of the effect of a node within the compressed length is exclusively possible with regard to concordant slendernesses and specimen sample numbers hence for specimen types A2 (no node, $\lambda = 3.3$) and B1 (one center node, $\lambda = 2.9$). The comparison shows a 9% higher $f_{c,0,mean}$ value for sample A2 without a node.

In average of test series A2 to B2 comprising a slenderness range of 2.4 to 12.6 the mean compressive strength and coefficient of variation evolved as

$f_{c,0,\,mean} = 55.3 \pm 7.8$ N/mm², COV = 14,1%.

The 5%-quantile value derived acc. to EN 14358 [16] by assumption of a log-normal distribution results in ($k_s = \frac{6.5\cdot n+6}{3.7\cdot n-3} = 1{,}87$, with n = 26 as the number of specimens)

$f_{c,0,05} = 41.9$ N/mm².

Table 3: Statistical evaluation of the ZERI compression test results

speci-men type	**specimen length**	**slender-ness ratio λ_{mean}**	**No. of tests**	**compressive strength $f_{c,0}$**				
				mean	**± std.**	**COV**	**5%-quantile**	**min**
	[mm]	[-]		[N/mm²]		[%]	[N/mm²]	[N/mm²]
A1	50	1.5	6	69.9	8.7	13	50.9	55.2
A2	100	3.3	9	56.7	7.8	14	42.3	47.4
A3	200-320	7.3 (4.7-12.6)	8	55.8	8.4	15	39.3	43.8
B1	100	2.9	6	52.0	8.3	16	35.9	43.2
B2	320-394	8.2	3	56.2	7.5	14	35.9	47.5
all (without type A1)	100-394	5.0	26	55.3	7.8	14	42.0	43.2

The effect of specimen length and of slenderness ratio are depicted in Fig. 5 a and b. Regarding all specimen types A1 to B2 a weakly correlated trend ($R^2 \approx 0.1$) towards lower strength values can be seen. However, when specimen type A1 and hence the very small slenderness ratios $\lambda < 2.3$ are excluded, what is sensible from above discussion on specimen type A1, then no correlation of compressive strength with specimen length and especially with slenderness ratio λ is observed (see dotted regression line).

The eventual impact of the preservation treatment used at ZERI specimen shipment 1 is assessed by a comparison of the specimens of shipment 1 and 2 (no treatment) omitting the specimen types A1 in both cases. The averages of both samples are 55.0 and 55.9 N/mm², i.e. no treatment effect can be concluded from the tests, whereby the small sample size of the non-treated sample has to be bared in mind.

The compressive modulus of elasticity was measured at 12 specimens comprising each specimen type except A1 with a majority of A3 specimens (5/12). The mean (± std) and minimum values evolved as

$E_{c,0,mean}$ 18524 ± 2178 N/mm² and $E_{c,0,min}$ = 15583 N/mm².

The density of the specimens not measured extensively was in average 824 kg/m³ at a moisture content of 12%. Note: The density influence was regarded in more depth at the below discussed DIHAD experiments.

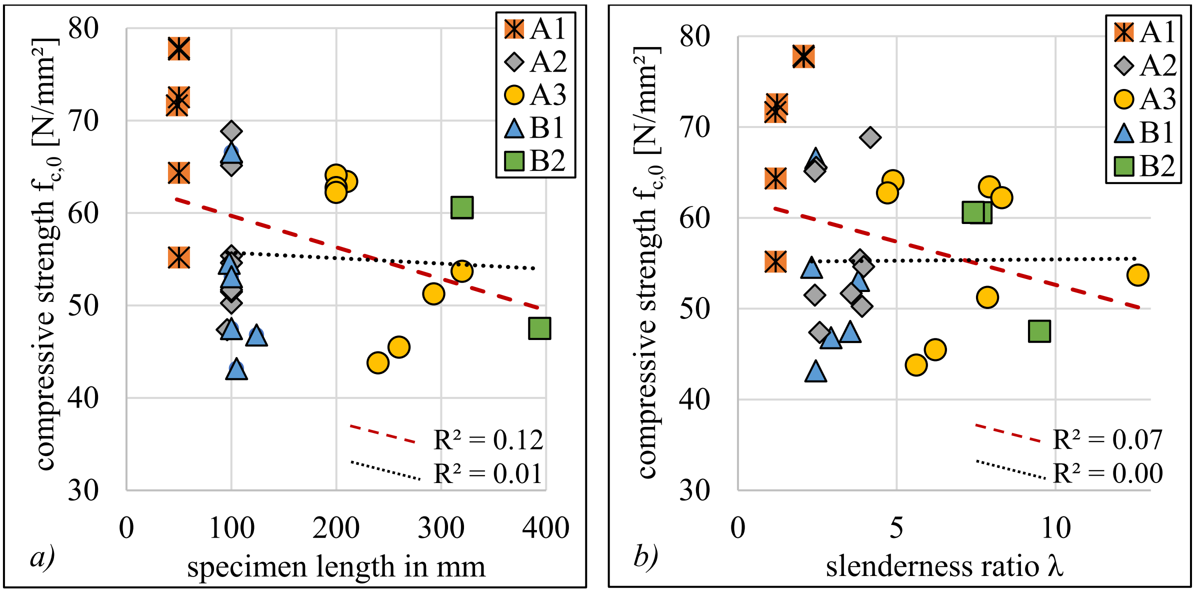


Fig. 5: ZERI compressive strength test results depending on a) specimen length, b) slenderness ratio

5.3 DIHAD bamboo

A statistical summary of the DIHAD bamboo compression tests separately for specimen groups I – III and for the entity of all specimens is given in Table 4 a and b for compressive strength and MOE, respectively. The mean values for all specimen groups I - III for compressive strength and MOE evolved as

$f_{c,0,mean} = 54.0 \pm 8.7$ N/mm² and $E_{c,0,mean} = 19824 \pm 4160$ N/mm².

The characteristic 5% quantile value of compressive strength derived according to EN 14358 assuming a lognormal distribution evolved as

$$f_{c,0,05} = 39.9\ N/mm^2.$$

The scatter of the strength and MOE values (all specimens) is denoted by COVs of 16% and 21%, respectively. It can be observed from Figure 6 that the compressive strength reveals a clear, however weakly correlated trend towards lower strength values with increasing cross-section area A (in mm²)

$$f_{c,0} = -0.003 \cdot A + 66.43 \quad (R^2 = 0.19). \tag{7}$$

So very roughly, an area increases by a factor of two, say from 3000 mm² to 6000 mm², leads to a strength decrease of about 15%. Regarding the effect of nodes, the following was found. In case of specimens cut from a single culm, specimens without a node showed in average a 5% higher compressive strength as compared to specimens with a center node. When looking at the different specimen groups I, II and III with coinciding slenderness ratios of 3.2 but partly significantly different culm wall thicknesses and outer diameters throughout higher strength values were obtained for specimens without a node, too. However, the ratio $f_{c,0,mean,no\ node}$ / $f_{c,0,mean,with\ node}$ decreased significantly with increasing diameter D, culm wall thickness δ and hence area. So, in case of specimen group I ($D_{mean} = 97.3$ mm, $\delta_{mean} = 11.6$ mm and $A_{mean} = 3123$ mm²) the regarded strength ratio was in average 1.10, whereas in case of group III specimens ($D_{mean} = 134.6$ mm, $\delta_{mean} = 16.3$ mm and $A_{mean} = 6050$ mm²) the strength ratio reduced to 1.013.

Compressive MOE shows almost no relationship with area A ($R^2 = 0.02$) whereby in contrast to compressive strength a very minor positive trend of $E_{c,0}$ vs. A is encountered (see Fig. 7). Similar as in case of compressive strength when regarding a single culm $E_{c,0}$ is about 9% higher without a node in the test specimen.

An effect of the specimen length and slenderness ratio on compressive strength could hardly be analyzed because the lengths equaled throughout outer diameter D according to ISO 22157 and differed by maximally 40 mm, resulting in a very narrow slenderness band of 2.6… **3.3**… 4.0.

The mean density of the DIHAD compression specimens was 753 kg/m³ at a moisture content of 12%. The impact of density on compressive strength is depicted in Fig. 8. With higher densities an increasing, moderately correlated compressive strength can be observed (ρ_{12} in kg/m³)

$$f_{c,0,12} = 0.042 \cdot \rho_{12} + 22.45 \quad (R^2 = 0.25) \tag{8}$$

Oppositely no impact ($R^2 = 0$) of density on $E_{c,0}$ was found.

Table 4a: Compilation of compressive strengths of investigated DIHAD specimens

specimen (sub) group (node presence)	**outer mean diameter** nominal (effective)	**slenderness ratio** λ_{mean}	**No. of spec**	**compressive strength $f_{c,0}$**				
				mean	**± std.**	**COV**	**5%-quantile**	**min**
	[mm]	[-]		[N/mm²]		[%]	[N/mm²]	[N/mm²]
I (node)	100 (97.3)	3.4	9	55.1 ±	6.3	11.5	43.2	47.4
I (no node)			9	61.1 ±	13.3	16.9	42.4	45.2
II (node)	130 (132.2)	3.1	9	50.2 ±	6.2	12.3	38.9	44.1
II (no node)			9	52.1 ±	10.5	20.1	34.5	41.5
III (node)	140 (134.6)	3.4	9	52.4 ±	7.1	13.5	38.4	38.6
III (no node)			9	53.1 ±	8.5	16.0	35.2	33.2
all	(120.8)	3.3	54	54.0 ±	8.7	16.1	39.9	33.2

Table 4b: Compilation of compressive MOEs of investigated DIHAD specimens

specimen (sub)group (node presence)	**outer mean diameter** nominal (effective)	**slenderness ratio** λ_{mean}	**No. of spec**	**Modulus of elasticity** $E_{c,0}$				
				mean	**± std.**	**COV**	**5%-quantile**	**min**
	[mm]	[-]		[N/mm^2]		[%]	[N/mm^2]	[N/mm^2]
I (node)	100 (97.3)	3.4	8$^{*)}$	17499 ±	3640	21%	11373	14001
I (no node)			9	19388 ±	4273	22%	11988	14155
II (node)	130 (132.2)	3.1	9	18605 ±	4848	26%	10785	13419
II (no node)			9	20312 ±	2869	14%	14377	13948
III (node)	140 (134.6)	3.4	9	20747 ±	3613	17%	13494	13808
III (no node)			8$^{*)}$	22418 ±	4831	22%	13208	14327
all	(120.8)	3.3	52	19824 ±	4160	21%	13116	13419

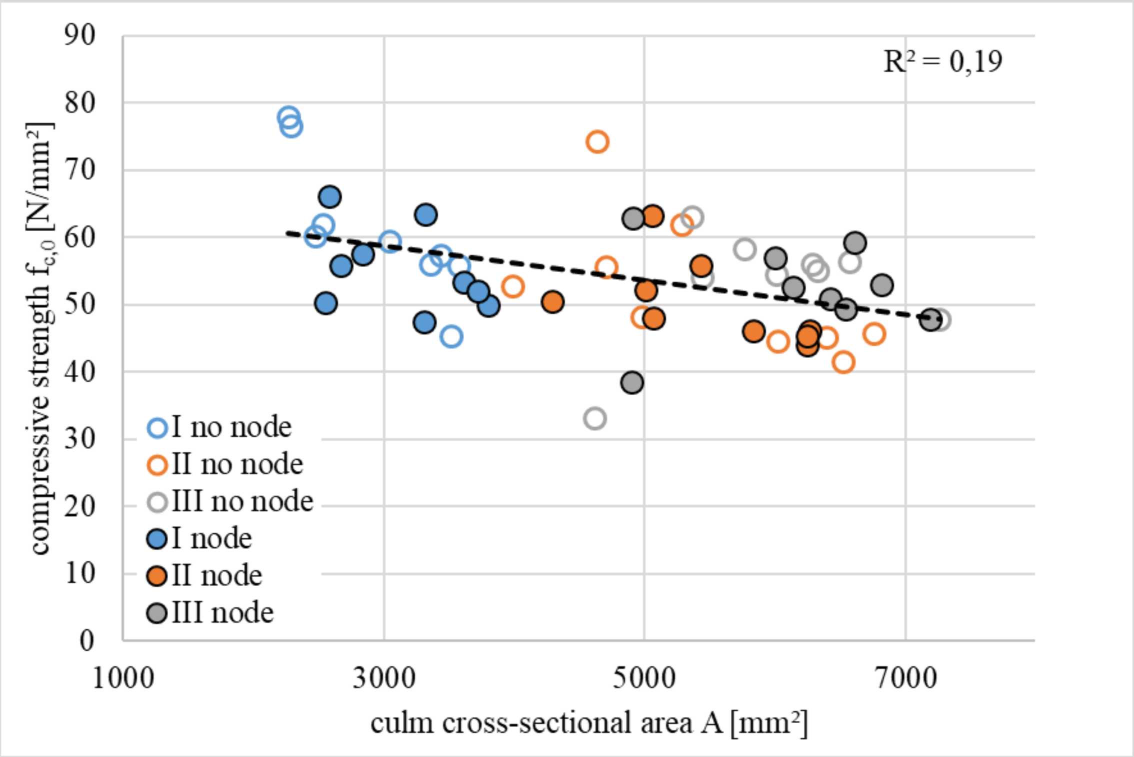


Fig. 6: Compressive strength $f_{c,0}$ depending on the specimen cross-sectional area for the six (sub)groups I – III with and without a node present

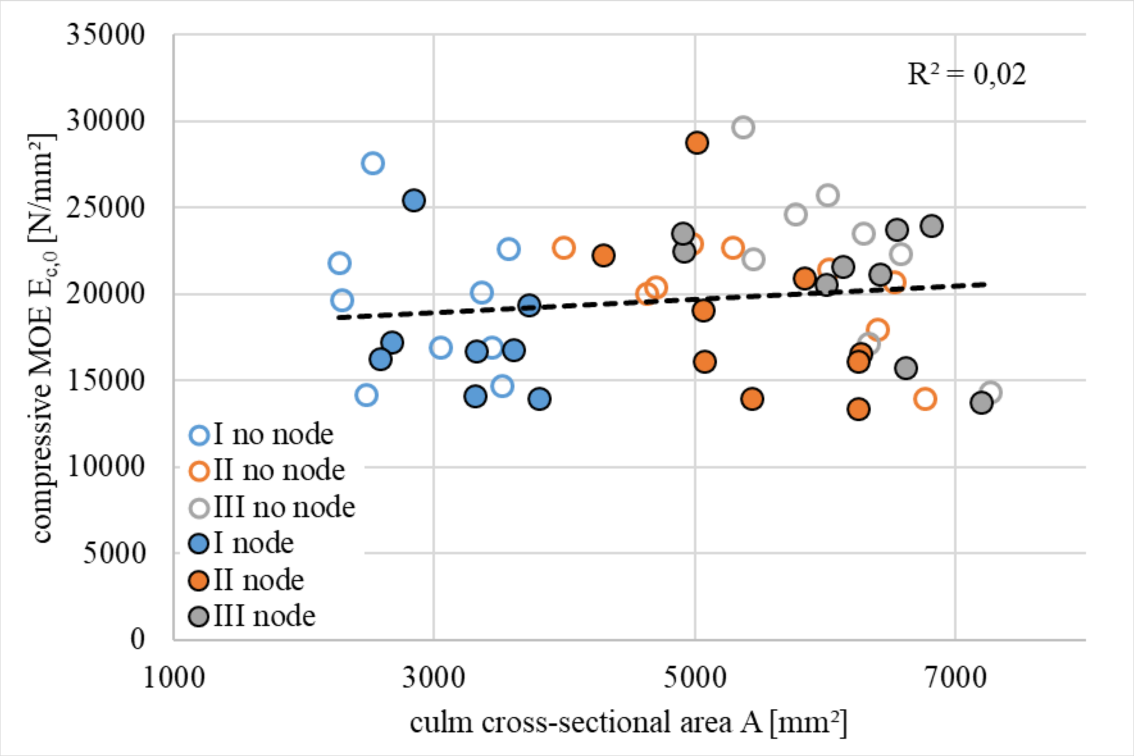


Fig. 7: Compressive MOE $E_{c,0}$ depending on the specimen cross-sectional area for the six (sub)groups I – III with and without a node present

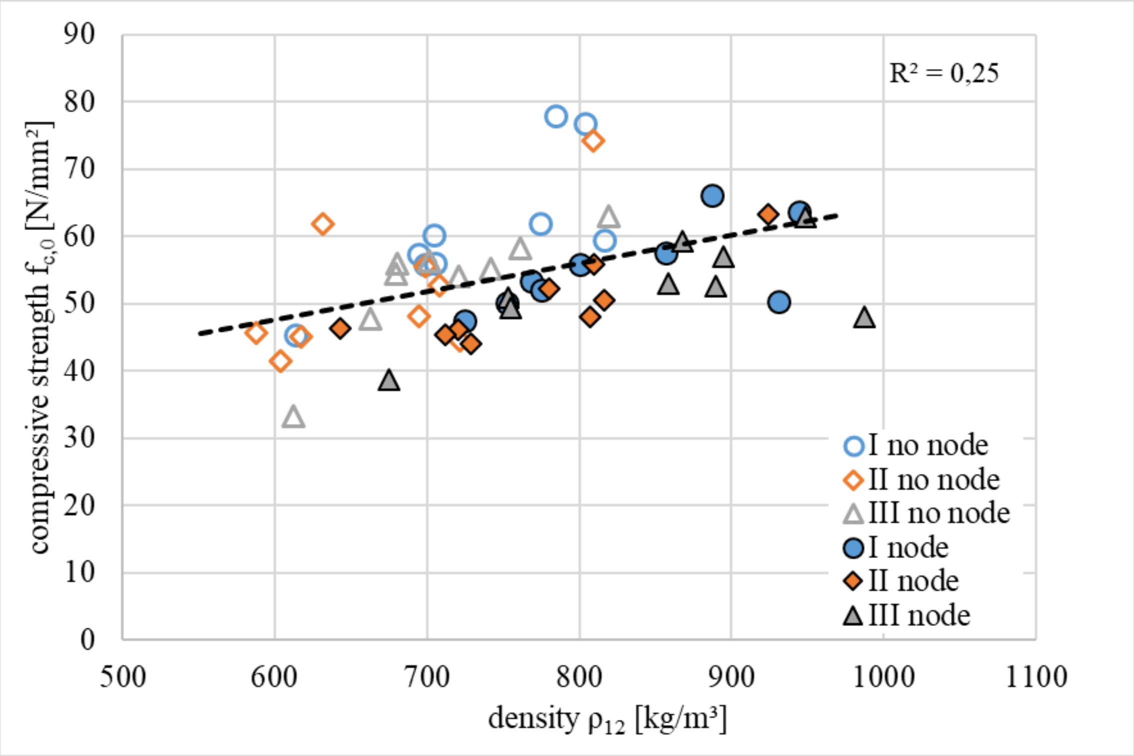


Fig. 8: Compressive strength $f_{c,0}$ depending on the specimen density for the six (sub)groups I – III with and without a node present

6. COMPARISON OF ZERI AND DIHAD PAVILION TEST RESULTS

The comparison of the former ZERI Pavilion bamboo tests with the recent DIHAD Pavilion compression tests shows an excellent agreement regarding compressive strength. On the mean and characteristic level, the ZERI (without type A1) and DIHAD strengths differed marginally by 2% and 5%, respectively:

$f_{c,0,mean,ZERI} = 55.3$ N/mm² and $f_{c,0,mean,DIHAD} = 54.0$ N/mm² and

$f_{c,0,0.5,ZERI} = 41.9$ N/mm² and $f_{c,0,0.5,DIHAD} = 39.9$ N/mm².

A comparable slightly less good agreement can be observed for the mean modulus of elasticity. Considering all specimen types or groups (ZERI A2, A3, B2 and B3 and DIHAD I, II and III) the results are:

$E_{c,0,mean,ZERI} = 18500$ N/mm² and $E_{c,0,mean,DIHAD} = 19800$ N/mm².

However, as revealed above, there is a slight trend towards higher MOE with increasing culm cross-section area (see Fig. 7). This should be considered bearing in mind that the DIHAD culms showed a specimen group III with rather high nominal and effective diameters and wall thicknesses ($D_{eff,mean} = 134.6$ mm and $\delta_{eff,mean} = 16.3$ mm) and hence a rather high area $A_{eff,mean} = 6057$ mm². Contrary, ZERI shipments 1 and 2 showed mean effective areas of 4100 mm² and 3000 mm², respectively, representing 67% and 50% of the mean of the DIHAD III cross-sectional size. Excluding the group III from the comparison as size and geometry wise not represented in the ZERI investigations, the mean MOE of the DIHAD investigations (groups I and II) reduces to

$E_{c,0,mean,DIHAD,I,II} = 18700$ N/mm²,

which then agrees extremely well with the ZERI bamboo MOE mean of 18500 N/mm².

7. CONCLUSIONS

Two extensive experimental investigations into the compression behavior parallel to culm axis of Columbia grown Guadua angustifolia bamboo forwarded almost coinciding results. Compressive strength and modulus of elasticity of culms with comparable cross-sectional dimensions yet unknown growth area within the country of origin (Columbia) do not differ although the sampling and testing is separated by more than two decades and the growth regions could be quite distanced.

This indicates clearly that the specification of a safe lower boundary (5%-quantile) for compressive strength and of a characteristic mean value for modulus of elasticity can be proposed tentatively for this bamboo species and country of origin:

$f_{c,0,k} = 40$ N/mm² and $E_{c,0,mean} = 18500$ N/mm².

The specified $f_{c,0,k}$ and $E_{c,0,mean}$ values should be restricted to mean and characteristic densities of $\rho_{12,mean} = 680$ kg/m³ and $\rho_{12,k} = 600$ kg/m³ as well as outer culm diameters and wall thicknesses of $D \geq 75$ mm and $\delta \geq 8.0$ mm.

Regarding applicability of the proposed design values to preservative treated culms it was proven that the preservation treatment according to a specific Japanese smoke exposure method shows no influence on compressive strength and stiffness parallel to culm axis. This can indirectly be assumed for a sodium pentaborate treatment, too.

Nodes located roughly at mid-length of the compression specimens reduced the compression strength vs. node-free specimens by maximally 10%. However, the strength decrease by nodes is highly dependent on culm diameter D, wall thickness δ and hence wall area A and reduced at large D, δ and A values of about 130 mm, 15 mm and $A \gtrsim 5000$ mm² to a negligible quantity. It has to be mentioned that the results related to the effect of nodes clearly differ trend- and magnitude-wise with findings in previous research [8] and [10]. A possible explanation is that the effect of nodes could be highly dependent on bamboo species. This has to be followed up in further investigations.

Density ρ is positively, however weakly correlated ($R^2 = 0.25$) with compressive shape strength as evaluated here. A multivariate regression of culm wall clear compressive strength vs. density, culm wall diameter and thickness would certainly forward a higher coefficient of correlation. Contrary, MOE $E_{c,0}$ seems to be rather unaffected by density what is rather unexpected and deserves a more profound investigation.

The specimen geometry, more precise the ratio of specimen length vs. outer diameter, termed aspect ratio, represents a highly important parameter in compressive tests especially of a natural material with rather low stiffness and growth-related defects. In structural timber compression tests parallel to fiber the specimen length and the center gauge length for MOE measurements are specified as 6xB and 4xB, whereby B is the smaller of both edge lengths of a rectangular cross-section. Within the two reported and compared bamboo test series the aspect and slenderness ratios l/D and λ varied from 0.5 – 4 and 1.5 to 12.6, respectively. The bamboo test standard ISO 22157 specifies for structurally relevant diameters D > 20 mm an aspect ratio $l/D \leq 1$, disregarding the interaction of culm diameter D and wall thickness δ. However, in tests of a hollow cylinder segment the specimen shape requirements have to address both geometry parameters D and δ simultaneously. Consequently, slenderness ratio λ according to basic mechanics seems to be the most appropriate parameter and hence λ is proposed here for an amendment of ISO 22157. As individual λ values in the range of 2.4 to 12.6 did not evidence an influence on compressive shape strength a slenderness ratio band width λ of the test sample mean in the range of 3 to 8 seems to be reasonable. The justification of a slenderness band width vs. a fixed value is bound to test reasons to enable a constant test specimen length for a sample with varying D and δ values.

A difficulty regarding bamboo strength classification consists in the fact that a test with a bamboo culm section forwards a shape strength affected by geometrical properties rather than an intrinsic material property. So, the upscaling of material properties gained from small clear sliced wall specimens to macroscopic behavior poses a future scientific challenge to pave the way for an increased bamboo use outside of their countries origin.

8. ACKNOWLEDGEMENTS

Many thanks are indebted to the former ZERI foundation for their priority consent to publish the data derived for realization of the ZERI bamboo pavilion at Expo 2000 in Hannover. The cast, of so far publicity disclosed results will foreseeable contribute to a much wider database necessary for understanding and classifying bamboo as an internationally acknowledged reliable engineered green material resource. Similar thanks belong to Nickl & Partner Architects and Werner Sobek Engineers for their immediate willingness to share the building project related data and hereof drawn conclusions with a world-wide engineering community for the sake of enhanced use of bamboo in structural applications.

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