Goli *et al. J Wood Sci* (2019) 65:4
https://doi.org/10.1186/s10086-019-1781-9

Journal of Wood Science

ORIGINAL ARTICLE Open Access

Thermal expansion of wood at different equilibrium moisture contents

Giacomo Goli[1], Francesca Becherini[2*], Maria Concetta Di Tuccio[2], Adriana Bernardi[2] and Marco Fioravanti[1]

Abstract

The measurement of wood thermal expansion at fixed values of moisture content (MC) between the dry state and the cell wall saturation point is a very difficult task, as MC varies with temperature. Being hygroscopic deformations much larger than thermal ones, in order to evaluate the latter, when changing temperature also relative humidity should be adapted. To achieve this goal a special apparatus was designed to vary relative humidity as a function of temperature to keep MC constant, and thus to measure the thermal expansion coefficient without hygroscopic effects. The moisture content was assessed to remain constant by testing the heating cycle of each specimen, keeping the specimen itself on a precision balance before the thermal expansion measurement. The radial coefficients of thermal expansion of ten specimens of Norway spruce were measured at 7.0% and 11.4% MC. No statistically significant differences were found between the two data sets, indicating a negligible effect of moisture content on wood thermal expansion at MC values typical of indoor environments. However, the thermal expansion coefficients measured at 7.0% and 11.4% MC seem to be higher than the values for dry state reported in literature, indicating an effect of the moisture content.

Keywords: Norway spruce, Moisture content, Thermal expansion coefficient, Wood

Introduction

The thermal expansion of wood has been extensively investigated since the last century. A short review of previous studies is presented in this section and the key findings summarized in Table 1, with the aim of setting the background of the research described in the present paper.

Early studies were performed by Villari [1] that measured the coefficient of thermal expansion (α) of several species (silver fir, chestnut, poplar, pine, walnut, etc.) in transversal (α_{trasv}) and longitudinal (α_{lon}) directions in dry state. With increase in temperature (T) from 2 °C to 34 °C, α_{trasv} increased from 5 up to 25 times α_{lon}. Later, Glatzel [2] measured α_{lon} and found results in agreement with those of Villari [1]. Hendershot [3] reported the values of α_{lon} and α_{trasv} in the dry state of several species, but at the same time he tried to evaluate the effect of moisture content by measuring α_{trasv} at 4% MC and α_{lon} at 5% MC for white pine. The author himself stated that these measurements could be affected by relevant errors, due to the difficulty of keeping MC constant, as it varies with temperature. However, according to the results, α_{trasv} did not change very much with a limited variation of moisture content.

Weatherwax and Stamm in a fundamental work [4] measured the thermal expansion coefficients of a number of American species and wood-derived products in the dry state. The authors reported the values of longitudinal, radial and tangential (α_t) coefficients of thermal expansion for two ranges of temperature variations, i.e., from 0 to 50 °C and from −50 to 50 °C. The coefficients showed a linear relation with density, but did not show significant changes for both T ranges. For species characterized by a density comparable to Norway spruce, the species studied in the present work, Weatherwax and Stamm [4] reported the following values of α_r: 23.8×10^{-6} K^{-1} for Sitka spruce and 21.9×10^{-6} K^{-1} for white fir with specific gravity at dry state (G_0) of, respectively, 420 kg/m^3 and 400 kg/m^3. The first systematic experimental work aimed to investigate the thermal expansion coefficient at different moisture contents and thermal ranges for several

*Correspondence: f.becherini@isac.cnr.it
[2] Istituto di Scienze dell'Atmosfera e del Clima, Consiglio Nazionale delle Ricerche, Corso Stati Uniti 4, 35127 Padua, Italy
Full list of author information is available at the end of the article

Table 1 Measured values of the thermal expansion coefficients of different wood species according to previous studies

Author	Year	Species	α_{lon} (10^{-6} K^{-1})	α_{rad} (10^{-6} K^{-1})	α_{tan} (10^{-6} K^{-1})	α_{trasv} (10^{-6} K^{-1})	MC
Villari	1868	Boxwood	2.6	/	/	61.4	Dry
Villari	1868	Silver fir	3.7	/	/	58.4	Dry
Villari	1868	Oak	4.9	/	/	54.4	Dry
Villari	1868	Pine	5.4	/	/	34.1	Dry
Hendershot	1924	White pine	3.65	/	/	63.6	Dry
Hendershot	1924	White pine	/	/	/	72.7	4% MC
Hendershot	1924	White pine	4.00	/	/	/	5% MC
Hendershot	1924	Basswood	5.46	/	/	44.4	Dry
Hendershot	1924	Tulip poplar	5.95	/	/	42.9	Dry
Hendershot	1924	Hard maple	4.22	/	/	60.2	Dry
Hendershot	1924	White ash	11.00	/	/	45.8	Dry
Weatherwax	1956	Sitka spruce	3.52	23.9	34.6	/	Dry 0/50 °C
Weatherwax	1956	Sitka spruce	3.15	23.8	32.3	/	Dry — 50/50 °C
Weatherwax	1956	White fir	3.90	21.7	31.6	/	Dry 0/50 °C
Weatherwax	1956	White fir	3.34	21.8	32.6	/	Dry — 50/50 °C
Weatherwax	1956	Douglas fir	3.52	27.1	45.0	/	Dry 0/50 °C
Weatherwax	1956	Douglas fir	3.16	27.9	42.7		Dry — 50/50 °C
Kubler	1973	Redwood	6	21	28	/	Dry 0/50 °C
Kubler	1973	Redwood	7	31	53	/	12% MC 0/50 °C
Kubler	1973	Redwood	−4	−5	−12	/	MC > 60% 0/50 °C
Kubler	1973	Douglas fir	6	24	29	/	Dry 0/50 °C
Kubler	1973	Douglas fir	10	38	38	/	12% MC 0/50 °C
Kubler	1973	Douglas fir	10	9	9	/	MC > 60% 0/50 °C
Kubler	1973	Red oak	9	26	32	/	Dry 0/50 °C
Kubler	1973	Red oak	8	44	70	/	12% MC 0/50 °C
Kubler	1973	Red oak	0.3	0	0	/	MC > 60% 0/50 °C
Salmén	1990	Norway spruce	/	−32	/	/	FSP T < 63 °C
Salmén	1990	Norway spruce	/	6	/	/	FSP T > 63 °C
Pizzo	2002	Norway spruce	< 2	/	/	27.7	12% MC
Pizzo	2002	Iroko	< 2	/	/	31.9	12% MC
Wood handbook	2010	Norway spruce	3.1/4.5	23.56	32.06	27.81	Dry G_0 = 422 kg m^{-3} calculated value

α_{lon} = coefficient of thermal expansion in longitudinal direction; α_{rad} = in radial direction; α_{tan} = in tangential direction; α_{trasv} = in generic transversal direction as reported by some authors, MC = moisture content. In the last column (MC) the thermal interval (e.g., 0/50 °C) means that the test was done between the two temperatures indicated

A G_0 of 422 kg m^{-3} corresponds to a density at standard environmental conditions of 450 kg m^{-3}

FPS fiber saturation point

species was carried out by Kubler et al. [5]. In the thermal range 0–50 °C, α_{lon}, α_r and α_t were studied for several species at three different moisture contents: dry state, 12% MC and MC > 60%. The coefficients showed a very heterogeneous behavior, as α_r and α_t were higher at 12% MC than at dry state [5]. Nevertheless, the data seemed to be not perfectly in accordance with those of other authors, as very little difference in the values of α_r and α_t for the same species was measured. For example, α_r and α_t were, respectively, 24×10^{-6} K^{-1} and 29×10^{-6} K^{-1} for Douglas fir in the dry state [5], while Weatherwax and Stamm [4] found $\alpha_r = 27.1$ 10^{-6} K^{-1} and $\alpha_t = 45 \times 10^{-6}$ K^{-1}. The same for yellow birch was $\alpha_r = 26 \times 10^{-6}$ K^{-1} and $\alpha_t = 28 \times 10^{-6}$ K^{-1} [5] against $\alpha_r = 32.2 \times 10^{-6}$ K^{-1} and $\alpha_t = 39.4 \times 10^{-6}$ K^{-1} [4]. The value of α_{lon} was very small, therefore any relevant difference was recorded between dry state and 12% MC. Kubler et al. [5] also highlighted that at fiber saturation point (FSP), α_r and α_t were very small and negative (the specimens became smaller when heated) in the thermal range 0–65 °C; above 65 °C, α switched again to positive values. The same behavior was highlighted by Abe [6] who performed a wide research

on the thermal properties of wood and wooden materials, but he worked near the glass transition temperatures of polymers, thus at temperatures much higher than the ones of interest for the present research. The negative value of α above the FSP was confirmed by Salmén [7]: below the softening point of lignin (63 °C), the thermal expansion coefficient of Norway spruce was negative, while above the softening point it was positive. According to the author, this behavior was the result of a thermodynamic equilibrium between cellulose and water, leading to a migration of water from the cellulose to the water phase.

Few experiments on samples equilibrated at standard environmental conditions (temperature 20 °C and 65% relative humidity) were performed by Pizzo et al. [8] for Norway spruce and Iroko to compare α_{lon} and α_{trasv} of wood with those of different adhesives. The MC value was kept fairly constant during the measurement, as the sample was included in the quartz cylinder of the dilatometer plug with a rod that limited the exchanges of moisture. Results for Norway spruce indicated that α_{trasv} varied between 28×10^{-6} K^{-1} and 32×10^{-6} K^{-1}, while α_{lon} was not significant. The problem of keeping MC constant was again in evidence as a limit of this kind of research, consequently results could be affected by errors.

To the best of the authors' knowledge, no other papers have focused on the thermal expansion of wood at MC levels above the dry condition and below the FSP.

According to the Wood Handbook [9], α_{lon} in the dry state can be assumed between 3.1 and 4.5×10^{-6} K^{-1} regardless of the density of the species, while α_r and α_t are density dependent and can be calculated as follows:

$$\alpha_r = (32.4G_0 + 9.9)10^{-6}K^{-1}, \quad (1)$$

$$\alpha_t = (32.4G_0 + 18.4)10^{-6}K^{-1}, \quad (2)$$

where G_0 is the specific gravity in the dry state. For Norway spruce, given a density at standard environmental conditions of 450 kg/m^3 [10] and a specific volumetric shrinkage coefficient of 0.39% [10], the corresponding specific gravity in the dry state (G_0) is about ~ 422 kg/m^3. For this value of G_0, α_r can be computed to be 23.56×10^{-6} K^{-1} and α_t to be 32.06×10^{-6} K^{-1}. Their average of 27.81×10^{-6} K^{-1} is not far from the values in literature [8].

Hori and Wada [11] analyzed the thermal expansion coefficient of cellulose crystals above and below 180 °C, as well as the macroscopic anisotropic thermal expansion of wood related to the crystal structure of cellulose.

As this short review clearly documented, the thermal expansion has been considered during the years as a minor problem compared to the hygroscopic deformations of wood. This is absolutely expected, as the two phenomena have different orders of magnitude: for example, the highest value reported in Table 1 (white pine measured by Hendershot α_{trasv} 72.7×10^{-6} K^{-1}) indicates a thermal expansion of 0.07% of the initial length for a 10 °C variation (from 20 to 30 °C), while a 10% variation in relative humidity (with a tangential shrinkage coefficient of 12) would result in a deformation of 1.2% (17 times more).

Nevertheless, a better understanding of the role of temperature in the deformation of a wooden object is particularly important in the field of preventive conservation of cultural heritage where the establishment of the allowable ranges of microclimatic variations is fundamental for the development of a sustainable conservation strategy for wood artifacts and for the correct management of indoor environments. In particular, the separation of the thermal and hygroscopic effects could give important information on the behavior of the objects.

Research on the effect of temperature fluctuations on the dimensional response of wooden objects is rather lacking in literature, except for few papers such as [12, 13]. In particular, Goli et al. [13] measured $\alpha_r = 74 \times 10^{-6}$ K^{-1} for the ribs (maple wood) of a violin, quite far from the value of 28.4×10^{-6} K^{-1} measured by Weatherwax and Stamm [4] for sugar maple in the dry state, showing how this kind of measurement could be extremely difficult on a complex object.

While thermal expansion was massively studied in the dry state, the typical conservation conditions of wood specimens, i.e., at moisture content from 9 to 12%, have been rarely considered.

The measurement of the relation between the thermal expansion of wood and its moisture content is a very difficult task, as the wood equilibrium moisture content (EMC) is directly related to both the temperature and relative humidity (RH) of the surrounding air. Therefore, EMC changes with air T, even when maintaining RH constant. Thermal variations lead to moisture flows in wood and consequently to hygroscopic deformations (shrinkage and swelling). With these latter being much larger than thermal expansion, when changing T, RH should be adapted to keep MC constant. This is the reason why most of the studies on thermal expansion of wood were done in dry conditions or above the FSP.

In this framework, the main aim of the present paper is to investigate the contribution of thermal expansion to the dimensional changes of Norway spruce. A special apparatus was designed to measure the coefficient of thermal expansion in the radial direction for Norway spruce wood, keeping its MC constant at the values of 7.0 and 11.4%. Norway spruce was chosen because it is a species often used to build the belly of musical instruments that are very sensitive objects, where also minimal

deformations may have significant effect on the preservation of original varnishes in early instruments. Moreover, 7.0 and 11.4% MC values were selected as they represent the EMC at ambient temperature (i.e., 20 °C) and relative humidity, respectively, of 35% and 65%. This upper and lower RH values were set to include the recommended values for the conservation of wooden heritage objects in indoor environment such as those defined by the Italian Committee for standardization—UNI [14] or the Italian Ministry of Cultural Heritage and Activities [15].

Methods

Experimental device

The measurement of the wood thermal expansion was performed inside a $400 \times 400 \times 600$ mm^3 chamber purposely developed to have a fine control of air temperature and relative humidity (Fig. 1a). The chamber was in turn placed inside a controlled room with thermo-hygrometric conditions set at 20 °C T and 65% RH.

A heating element inside the chamber made the temperature vary between 25 and 45 °C. A temperature-controlled water recirculation circuit allowed water to be transported inside the precision chamber at a calibrated temperature to produce the vapor pressure suitable to get the desired relative humidity. The whole process was managed by a PID controller designed ad hoc in LabVIEW and controlled by the digital outputs of an NI USB PC board. The sensor used for the measurement of T and RH was a Sensirion SHT75, characterized by the following typical performance values in the operating ranges: 0.01 °C and 0.05% RH of resolution; ± 0.3 °C and ± 1.8% RH of accuracy; 0.1 °C and ± 0.1% RH for repeatability. The response time ($\tau = 63\%$) of the sensor was 8 s for RH and between 5 and 30 s for T. The chamber was tested to maintain temperature at 25 ± 0.2 °C and relative humidity at 65 ± 0.5%. Wood thermal expansion was measured with a Monitran LVDT transducer type MTN/EUGL000.5 with 1 mm stroke, ± 0.25% of accuracy (± 2.5 µm) and ± 0.1% of repeatability (± 1 µm) with integrated electronics and analogic output. The signal was acquired via a 16-bit resolution PC USB board at 1 kHz of sampling frequency and the data averaged every second to minimize noise. The measurement was performed inside an aluminum frame used to hold the wood sample and the transducer. The whole system was calibrated at different temperatures using a glass standard reference material for thermal expansion, the Borosilicate glass 731, with thermal expansion values certified by the National Institute of Standards and Technology. Once the system reached stable conditions, the measured noise was very small, i.e., ± 0.25 µm.

For the tests, ten specimens of Norway spruce (*Picea abies* L.) were prepared, 15 mm thick, 3 mm wide and 100 mm long. The mass of each specimen was measured by a Ohaus AP210S precision balance with 10^{-4} g resolution. The sample was placed inside the holder and measured along the radial direction. The average density of the ten specimens was 420.7 ± 20.9 kg/m^3 with a minimum value of 394.8 and a maximum value of 473.7 kg/m^3. The type of wood selected was characterized by an average ring width of 1.4 ± 0.04 mm with a minimum of 1.34 mm and a maximum of 1.46 mm.

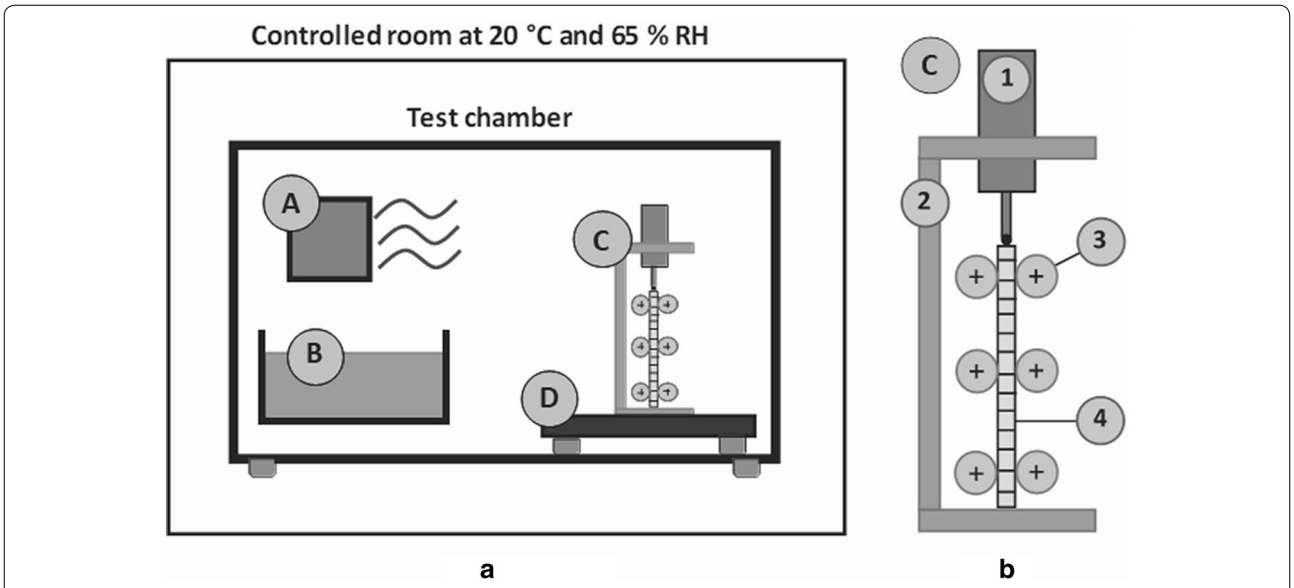

Fig. 1 **a** Test chamber with temperature (A) and relative humidity (B) regulation systems, measuring device (C) and dumped device holder (D); **b** Aluminum measuring device (C) with transducer (1), frame (2), sample holder allowing longitudinal movement (3), sample (4)

Measurement procedure

Thermal expansion was measured by varying T from 25 °C to 45 °C. To keep moisture content constant during the test, RH was varied with T. The couples of T–RH values that corresponded to a constant MC were determined making a pre-test where the temperature was varied while the sample was continuously weighted by a precision balance to check that no mass variation occurred. Different types of ramps were tested and finally the best was identified: 1 °C step every 600 s with an increase of 0.30% RH. This value was verified both with increasing and decreasing temperature to avoid hysteresis. The same result was obtained for all the specimens. To determine the thermal expansion coefficient at different wood moisture contents, two RH values were used as starting points at 25 °C: 35% and 65% RH. The temperature was increased from 25 °C to 45 °C, and at the same time RH reached 41% in the former case and 71% in the latter. The moisture content determined by gravimetric test was 7 ± 0.1% at 25 °C and 35% RH, and 11.4 ± 0.5% at 25 °C and 65% RH.

The thermal expansion coefficient was determined as follows:

$$\alpha = \frac{\Delta L}{L * \Delta T},$$

where ΔL is the length variation because of the thermal expansion for a given temperature variation ΔT and L the initial length of the specimen.

The ten specimens were all tested at both high and low relative humidity, and again the thermal expansion coefficient was determined both with increasing and decreasing temperatures. The test for each specimen was repeated three times and the six values obtained were averaged. At the end of each T cycle, the measured value of deformation was compared with the one measured at its beginning to verify that unexpected deformation did not occur.

Statistical analysis of data was performed with R 3.4.2 software for statistical computing.

Table 2 Values of radial thermal expansion coefficient (α_r) at 7.0 and 11.4% moisture contents

Moisture content		7.0%	11.4%
T range (°C)		20 °C → 45 °C	20 °C → 45 °C
RH range (%)		35% → 41%	65% → 71%
Specimen number	**Specimen ID**	**α_r (10^{-6} K^{-1})**	**α_r (10^{-6} K^{-1})**
1	A03	32.2	33
2	A05	34.7	32.3
3	A07	31.1	31.1
4	A09	27.1	31.9
5	A11	29.9	35.1
6	A12	30.9	30.7
7	A13	30.1	28.6
8	A14	32.5	36
9	A15	31.2	28.5
10	A16	28.9	31.2
	Average	30.9	31.8
	SD	2.1	2.4

Results and discussion

The measured values of thermal expansion coefficient are reported in Table 2 and plotted in Fig. 2. For each specimen, no relevant difference can be observed between the values of thermal expansion coefficient calculated at 7.0 and 11.4% MC; moreover, the differences were randomly distributed.

Also the box plots in Fig. 3 do not show any notable difference between the two data sets.

Data were tested to be normally distributed by a Shapiro–Wilk normality test ($p = 0.977$ for MC 7.0% and $p = 0.627$ for MC 11.4%) and homoscedastic by an F test ($p = 0.644$). Then, a Student's t test for paired data was applied ($p = 0.308$). The results of the statistical analysis performed on the two data sets indicated that the differences of the thermal expansion coefficients calculated at 7.0 and 11.4% MC were not statistically significant at 95% confidence level.

The expected value of α_r, calculated with Eq. (1), with a measured density of 420.7 kg/m^3, corresponding to a G_0 of 394.1 kg/m^3, was $\alpha_r = 22.7 \times 10^{-6}$ K^{-1}. This value is related to the dry state, while the values obtained through the experiment described in this paper are related to 7.0% and 11.4% MC. The calculated value of α_r in the dry state is in agreement with the values of α_r for Sitka spruce and white fir measured by Weatherwax and Stamm (Table 1) and lower than the values we have measured, respectively, at 7.0% and 11.4% of moisture content.

Conclusions

The special apparatus designed to investigate the dimensional changes of wood due to thermo-hygrometric variations at constant moisture content allowed to measure the radial thermal expansion coefficient of Norway spruce at 7.0% and 11.4% MC, corresponding to environmental conditions of 25 °C and 35% RH and 25 °C and 65% RH, respectively. These thermo-hygrometric conditions and the related wood moisture contents are typical values of indoor environments.

The average values of α_r, calculated as an average of ten experimental replicas, were, respectively, $\alpha_r = 30.9 \times 10^{-6}$ K^{-1} at 7.0% MC and 31.8×10^{-6} K^{-1} at

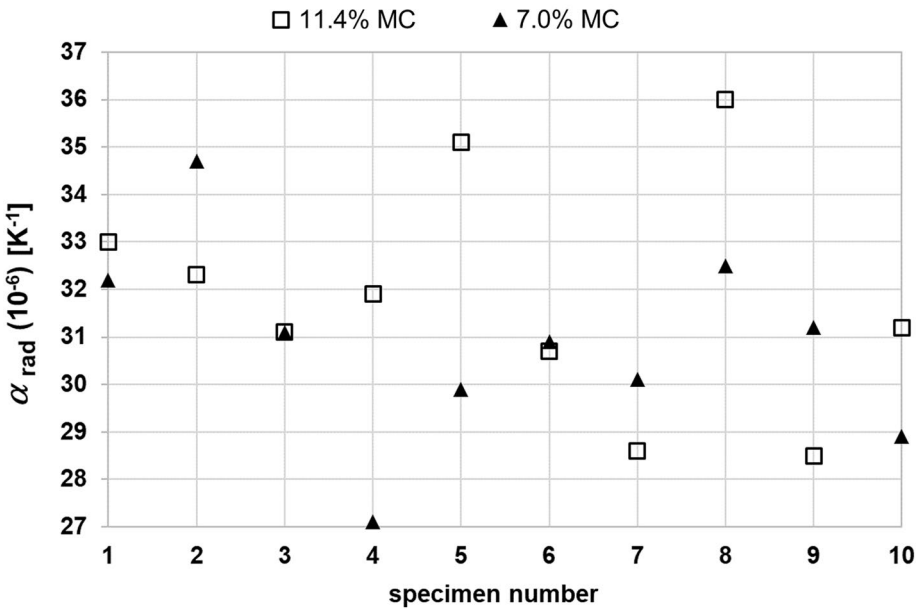

Fig. 2 Calculated values of thermal expansion coefficient for each of the ten specimens at two moisture contents: 7.0% solid triangles, 11.4% empty squares

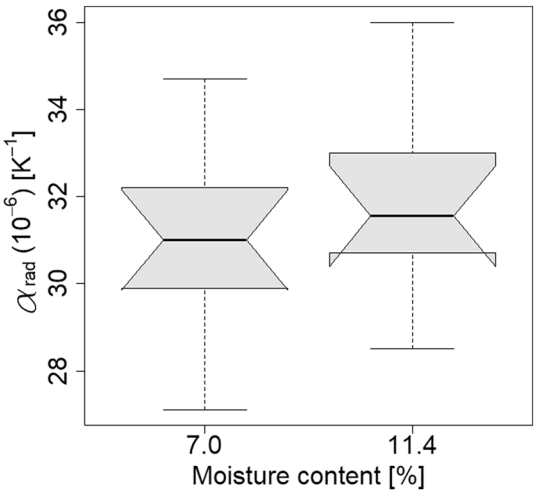

Fig. 3 Box plots of the coefficients of thermal expansion at 7.0 and 11.4% of moisture content. The black line inside the box is the median value, the upper and lower lines of the box are the first and third quartiles, the upper and lower lines are the maximum and the minimum values, and the notches are the 95% confidence interval of the medians

11.4% MC. The difference between the two data sets measured at the two moisture content values was not statistically significant.

Nevertheless, both values are slightly higher than the ones reported in literature for the same wood species in the dry state. This result seems to confirm a role of the wood moisture content in its thermal expansion, but this effect can be considered negligible in typical indoor environments, characterized by thermo-hygrometric conditions and related MC included in the ranges investigated in the present experiment.

Abbreviations

G_0: specific gravity at dry state; FSP: fiber saturation point; MC: moisture content; RH: relative humidity; *T*: temperature.

Authors' contributions

GG contributed to define and realized the experimental setup, the regulation systems and acquisition chain, performed the measurements, discussed the results and contributed to the conclusions. FB contributed to the experimental setup and statistical analysis, discussed the results, revised and managed the article and contributed to the conclusions. MCdT contributed to data analysis after each test. AB contributed to define the work plan, revised the paper and partly funded this research. MF conceived the study, contributed to define the research project and the experimental setup, and revised the paper. All authors read and approved the final manuscript.

Author details

[1] Dipartimento di Gestione dei Sistemi Agrari, Alimentari e Forestali (GESAAF), Università di Firenze, Via S. Bonaventura 13, 50145 Florence, Italy. [2] Istituto di Scienze dell'Atmosfera e del Clima, Consiglio Nazionale delle Ricerche, Corso Stati Uniti 4, 35127 Padua, Italy.

Acknowledgements

The authors acknowledge the Italian *Ministry for Education, University and Research* and Ing. Lorenzo Procino from GESAAF that contributed to design and realize the sample holder for the test.

Competing interests

The authors declare that they have no competing interests.

Availability of data and materials
The data sets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Consent for publication
Informed consent was obtained from all individual participants included in the study.

Ethics approval and consent to participate
This article does not contain any studies with human participants or animals performed by any of the authors.

Funding
Not applicable.

Publisher's Note

Received: 9 October 2018 Accepted: 11 December 2018
Published online: 11 February 2019

References

1. Villari EM (1868) Sur le propriétés physiques du bois conpé parallèlement ou transversalement aux fibres. Ann Chim Phys 14:503–504
2. Glatzel P (1877) Neue Versuche über die Ausdehnung von Körpern durch die Wärme. Ann Phys 236:497–514. https://doi.org/10.1002/andp.18772360402
3. Hendershot OP (1924) Thermal expansion of wood. Science 80(60):456–457. https://doi.org/10.1126/science.60.1559.456
4. Weatherwax R, Stamm A (1956) The coefficients of thermal expansion of wood and wood products. Forest products Laboratory, Madison
5. Kubler H, Liang L, Chang LS (1973) Thermal expansion of moist wood. Wood Fiber Sci 5:259–267
6. Abe F (1973) Studies on the thermal properties of wood and woody materials. IV. Thermal expansion for wood. Mokuzai Gakkaishi J Japan Wood Res Soc 19:69–74
7. Salmén L (1990) Thermal expansion of water-saturated wood. Holzforschung 44:17–19
8. Pizzo B, Rizzo G, Lavisci P et al (2002) Comparison of thermal expansion of wood and epoxy adhesives. Holz als Roh und Werkst 60:285–290. https://doi.org/10.1007/s00107-002-0295-z
9. USDA Forest Products Laboratory (2010) Wood handbook—wood as an engineering material 2010, 2010th edn. Forest Products Laboratory, Madison
10. CIRAD (2015) Tropix 7.0. https://tropix.cirad.fr/FichiersComplementaires/EN/Tempered/NORWAY%20SPRUCE.pdf
11. Hori R, Wada M (2005) The thermal expansion of wood cellulose crystals. Cellulose 12:479–484. https://doi.org/10.1007/s10570-005-5967-5
12. Bratasz Ł (2013) Allowable microclimatic variations for painted wood. Stud Conserv 58:65–79. https://doi.org/10.1179/2047058412Y.0000000061
13. Goli G, Fioravanti M, Busoni S et al (2012) Measurement and modelling of mass and dimensional variations of historic violins subjected to thermo-hygrometric variations: The case study of the Guarneri "del Gesù" violin (1743) known as the "Cannone". J Cult Herit 13:S154–S160. https://doi.org/10.1016/j.culher.2012.04.007
14. UNI (1999) UNI 10829: Beni di interesse storico e artistico. Condizioni ambientali di conservazione. Misurazione ed analisi. UNI, Milano
15. Ministero per i Beni e le Attività Culturali (2000) D. Lgs. n.112/98 art. 150 comma 6 - Atto di indirizzo sui criteri tecnico-scientifici e sugli standard di funzionamento e sviluppo dei musei