Mechanical characteristics of aged Hinoki (*Chamaecyparis obtusa* Endl.) wood from Japanese historical buildings

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Abstract

Wood is a material designed by nature to last, as long as it is free from biodeterioration. It can support trees for centuries, and as an engineering material it can again sustain loads for considerable periods. Wood has always played a major role in Japanese culture and is used in more than 90% of buildings listed as a National property or an important cultural property of Japan. Since 2004, the Kyoto University, Japan, has undertaken a project to compile a unique collection of wood samples from various temples and historical buildings. The paper deals with Japanese traditional ideas and dedication to selecting woods accorded to their technological compatibility and ability to transfer similar qualities for construction and maintenance,, and how wood identification can contribute in restoration of historical buildings in modern Japanese contexts. The paper also deals with mechanical characteristics of aged hinoki (Chamaecyparis obtusa) wood of Japanese historical buildings especially their Young's modulus and rapture energy.

Keywords

Aging, wood, historical buildings, mechanical properties, hinoki

Introduction

At the east end of the Silk Road, the islands called "The land of the rising Sun" makeup Japan. Many historical buildings over 1200-years-old still exist in Japan. The ancient capitals Kyoto and Nara have many traditional wooden buildings, some of which are also listed on the UNESCO World Cultural Heritage register. It is believed that the traditional architecture in Japan, for example, Buddhist temples, Shinto shrines and castles, is exclusive to the Japanese archipelago. Japanese architecture has many similar features to Chinese or Korean architecture, although the methodology of restoration of historic buildings is very different.

The Japanese government has been restoring and conserving historic buildings for110 years. Principally the restoration practice for historic buildings in Japan is characterized by its adherence to original techniques and materials, and also for its minimum replacement of members by new ones. As a result, it is represented by a selection of methods, which preserve the buildings for the future, without altering their structures and designs.

However it is not sufficient to apply recent scientific methods to understand these traditional techniques and materials. Since 2004, a collection of wood samples from various temples and other historical building has been gathered by at the Research Institute for Sustainable Humanosphere, Kyoto University, Japan (RISH). The aim of the project is to stimulate mutual cooperation between wood scientists and architectural conservators and to improve relations between them.

Wood is a material designed by nature to last, provided it is not attacked by biological agents. It can support trees for centuries, and as a technological material it can again sustain loads for considerable periods. It is, as a consequence, a major component of the cultural heritage of many civilizations and the assessment of wood properties from ancient objects and structures is a question of fundamental and practical interest [D. Fengel, 1991].

One major difficulty for such research is the gathering of suitable samples, with well-defined origin, certified dating and permission of publication by conservation administration. The Japanese context, where traditional uses of wood have been maintained for more than 1600 years, offers a unique opportunity to address the question of wood aging. Wood has always played a major role in Japanese culture. More than 90% or the nationally important properties of Japan are constructed with wood. The most famous and the world's oldest wooden construction still standing is Horyu-ji temple from the latter half of the seventh century. Since 2004, a collection of wood samples from various temples and other historical building has been gathered by the Research Institute for Sustainable Humanosphere of the Kyoto University (Japan), expanding a collection gathered in the 1950s by Jiro Kohara [1958].

The matching of specimens from different origins is another typical obstacle. Wood is a variable material due to genetic variations and dependency on growing conditions of the trees. To discuss property changes due to aging, a recent reference is required. However, it is difficult and sometimes impossible to obtain recent wood that closely matches a given old wood sample. To overcome this difficulty, well-established parameters relating to the structure and properties of wood can be used to produce corrections, thus allowing the comparison of data from slightly mismatched samples.

Kohara [1958] reported that the bending strength and rigidity of aged Hinoki wood, used in temple structures for over 1300 years, initially increased for a few hundred years and then subsequently decreased with time. This paper presents new results obtained on similar materials. Representative samples of wood that were free from biological attack, weathering and visible damage were selected. Thus the properties measured reflect the intrinsic aging of the material, resulting from the long-term action of moderate mechanical stress, temperature and humidity fluctuation, and air oxidation [D. Fengel. 1991]. The results of mechanical testing of specimens of increasing age will be presented and discussed in relation to the possibility to predict the consequence of natural aging on wood properties.

Materials and method

Wood identification of aged wood of historical buildings

Wood species used for building materials might change according to the era. Generally speaking, in Japan, initially hinoki (*Chamaecyparis obtusa* Endl) was mostly used for temple construction in Nara era (AD.710-AD.794). Afterwards keyaki (*Zelkova serrata* Makino) took that role for the temples after the Muromachi era (AD.1333-AD.1573). A document of Chronicles of Japan, NIHON-SHOKI, written in AD720 mentioned that hinoki wood had maintained its value as a building material since the beginning of 8th century.

However, determination of wood species by naked eye is difficult, especially in case of old timber. Even skilful carpenters sometimes make errors. This is the reason why wood species should be identified scientifically at least based on the microscopic features of wood.

Sample origins

The aged samples were Hinoki (*Chamaecyparis obtusa*) wood from Japanese historical buildings, mostly Horyu-ji temple in Nara. The specimens used in this study were cut from aged wooden members provided from the restoration sites, which were not reused. The modern wood used for comparison was taken from a 360 year old tree from Kiso region, where the highest quality Hinoki has been grown for the last 3 centuries, and selected according of craftsman viewpoint. It was cut in 1988 and had been subjected to slow drying for 19 years before testing in 2006. Sample labelling, origin, and basic structural information are given in Table 1. To avoid the effect of UV degradation and insects, the outer layers and nails were removed, and the specimens for mechanical testing were taken from the central portion of the samples. No sapwood occurrence was detected, so that all the studied material consisted of heartwood.

Age determination

To evaluate wood age, radioactive carbon dating ^{14}C and dendrochronology were used. For each sample the wood was processed as a board containing more than 60 tree rings. Tree ring dating was performed by comparing these ring patterns with a standard pattern available for Hinoki as far back as 912 BC [Mitsutani,T.,1990]. Distinct ring patterns of Hinoki enabled dating with yearly precision. For precision dating, ^{14}C wiggle-matching method was applied [Imamura, M., et al. 2007]. As shown in Table 1, the agreement between both methods was good: the difference between ^{14}C and dendro-date ranged from -40 to 29 years. These methods can only provide information about the wood age, defined as the time elapsed since wood formation in the tree. The analysis of colour variations in the same samples suggested that most of the aging occurred after wood processing [Yokoyama, M., 2009], so that the period of time separating wood formation and tree felling should be subtracted from the wood age for the analysis of aging processes. However, in most cases this information is not available, and the time elapsed since tree felling (t_T) cannot be calculated. For the subsequent analysis, an upper bound of t_T (time elapsed since tree felling) will be considered, based on the newest visible ring on the sample. For the most recent historical sample H and the reference I, this gives a direct estimate as the bark was included in the sample. For the older samples the relative error is likely to be small. In the following, this estimate of t_T will be designated as the “age” of the sample.

	Collection	Origin	Block dimensions (R x T x L, cm)	RW (mm)	Dendro chronology* (AD)	^{14}C interval dating* (AD)	t_W (yrs)	t_T (yrs)
A	KYOw2701, RISH	HYJ	11 x 3.4 x 10	0.8	343 / 434	367 / 458	1618	1583
B	KYOw2738, RISH	HYJ	7.0 x 4.2 x 10	0.5	458 / 612	418 / 572	1467	1405
C	private	HYJ (leg)	6.7x 11.5 x 47	0.9	400 /502	418 / 520	1548	1515
D	private	HYJ (leg)	7.5 x 11.5 x 55	0.8	431 /537	421 / 527	1530	1480
E	private	HYJ (leg)	9.5 x 13 x 42	0.7	584 / 792	587 / 795	1319	1225
F	private	HYJ (leg)	5 x 7.8 x 52	1.0	1029 / 1086	1000 /1059	899	931
G	private	HYJ (leg)	2.5 x 14 x 58	0.8	1106 / 1270	1098 /1262	822	747
H	(temple donation)	SJJ	1100 (∅) x 30 (L)	0.8	1069 / 1438	1071 / 1438	753	569
I	(workshop)	Kiso forest		1.0	1622 / 1988	1631 / 1973	200	19

HYJ = Horyuji temple, Nara ; (leg) = legend ; SJJ = Senjyuji temple, Mie ; RW =average width of annual rings ; * dates (A.D.) of first/last measured growth ring ; t_W = mean time elapsed since wood formation in the measured portion ; t_T = time elapsed since tree felling (estimated upper bound for samples A to G) ; t_W and t_T are estimated from dendro-dating.

Table 1: Origin and dating of the samples

Bending test

Wood is a highly anisotropic material, much more rigid and strong along fibres (longitudinal direction, L) than across fibres (radial direction, R, or tangential, T). Although the loading of beams is dominantly applied in L direction, in the connections parts a complex stress state occurs and the response to transverse loading may become critical. For that reason, 3 points bending tests were performed not only in L, but also in R direction whenever enough material was available. Matched specimens of dimensions 60 mm (L) × 10 mm (R) × 2 mm (T) were cut for L tests, 60 mm (R)×10 mm (T)× 2 mm (L) for R tests. The samples were initially dried at room temperature for 3 weeks in a desiccator with silica gel, then conditioned at 20°C and 60% relative humidity (R.H.). They were weighed before and after the tests performed in the air-dry condition, then oven dried at 60°C, 24 hours at atmospheric pressure and 24 hours in vacuum in presence of P_2O_5, and weighted again to calculate the moisture content during the test, as well as the oven-dry density and the air-dry density. The tests in L and R directions were performed on 5 to 10 specimens per sample and loading direction, with span length 50 mm and crosshead speed 5 mm/min.

Results and discussion

Stress-strain relationship

Fig. 1 shows typical stress-strain curves in L and R bending for each aged sample. In the following, the index L and R will be used to distinguish the value for each loading direction.

Our range of air dry density, 0.33~0.49 g/cm³ or of oven dry density, 0.32~0.46 g/cm³, almost covers that of modern hinoki [*Mokuzai Kogyou Handbook*. 2004, Imamura, H., et al. 1983]. As a general trend, aged wood appeared stiffer (higher E) and stronger (higher σ^m), at least in L direction, than the modern wood tested. As will be discussed below, this can be partly explained by differences in density and moisture content. The post-linear behaviour of aged wood, on the other hand, was clearly more brittle than in modern wood: this increase in brittleness, apparent from the curves of Fig. 1. All aged R specimens exhibited a fragile response, so that the elastic limit ε^e could only be estimated for the recent wood (sample I).

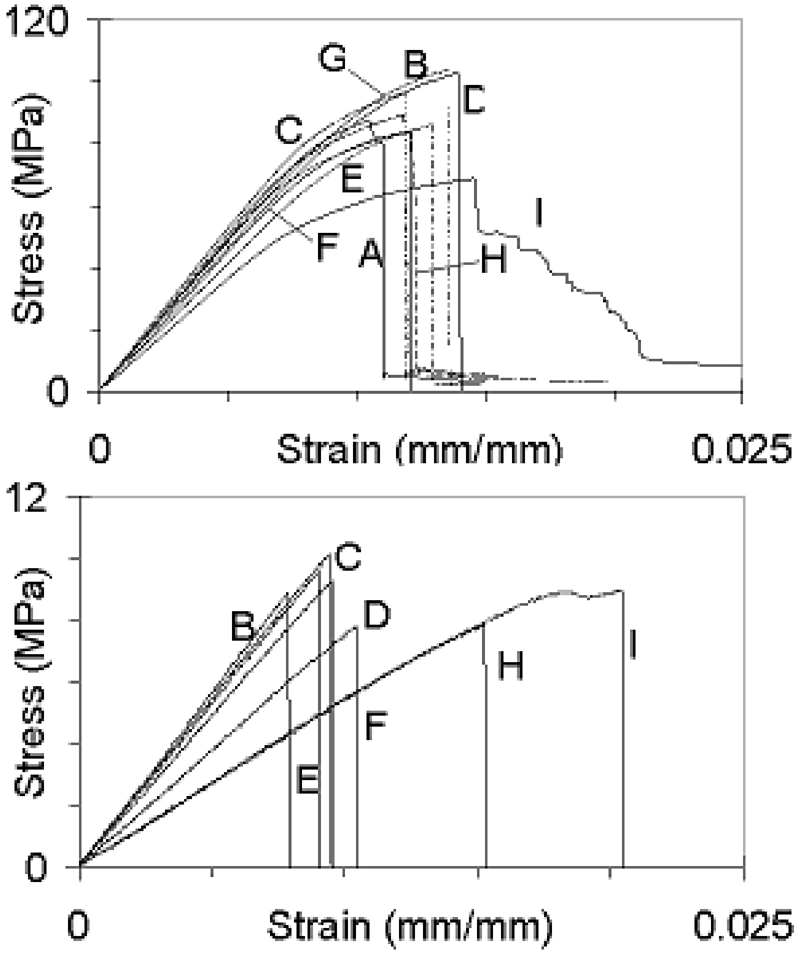

Fig.1 Typical stress-strain curves
Upper: L direction / Lower: R direction

Strain parameters

Fig.2 shows the effect on strain parameters, for which no correction was tried: the elastic limit (ε^e) in L direction and the breaking strain (ε^m) in L and R directions. A slight increase of ε^e_L, a slight decrease of ε^m_L , and a drastic decrease of ε^m_R were observed.

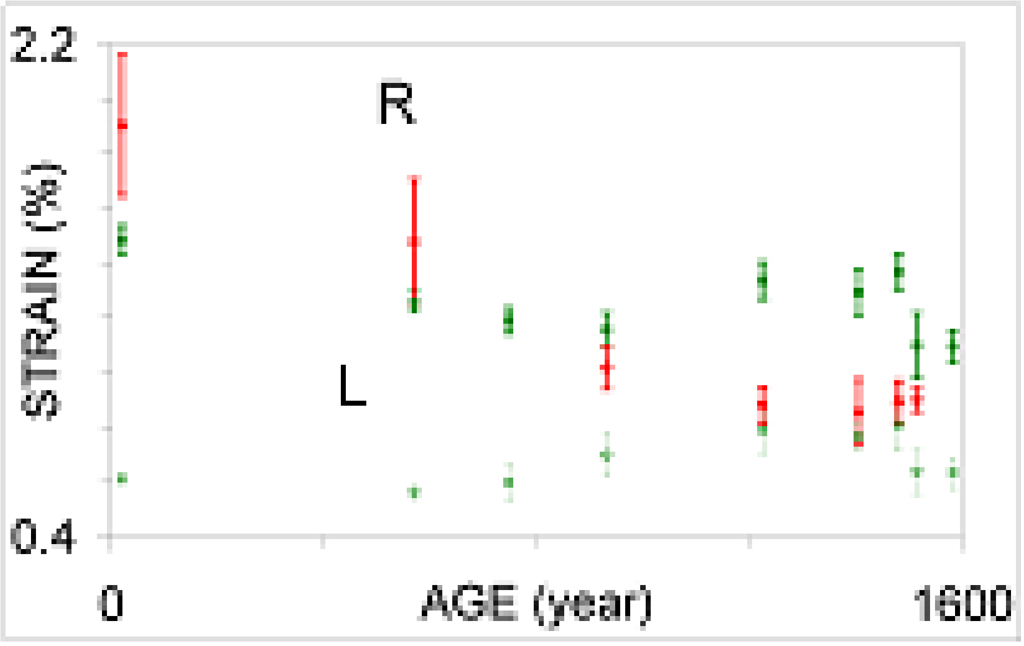

Fig.2 Relationships between strain and age.

The difference of behaviour between L and R directions can be explained by the structural organization of wood fibres.

The effect of aging on mechanical properties

Chemical analysis and thermo-mechanical testing performed in parallel to the present study. Fig.3 evidenced a decrease of hemi-cellulose content [Ragil, W., et al, 2007], as well as an increase of lignin cross-linking [Yokoyama, M., et al., 2007]. Similar observations were previously made on other aged wood by using FTIR [Takei, T., et al., 1997]. Hemicelluloses ensure the transverse cohesion between cellulosic microfibrils and lignin matrix, so that their degradation, especially in S_2, is also more detrimental to R than to L direction. The increase of cross-linking would increase the brittleness of lignified parts, especially in the middle lamella, thus accounting for the drastic decrease of R toughness without inducing any drop in rigidity [Yokoyama, M., et al, 2009].

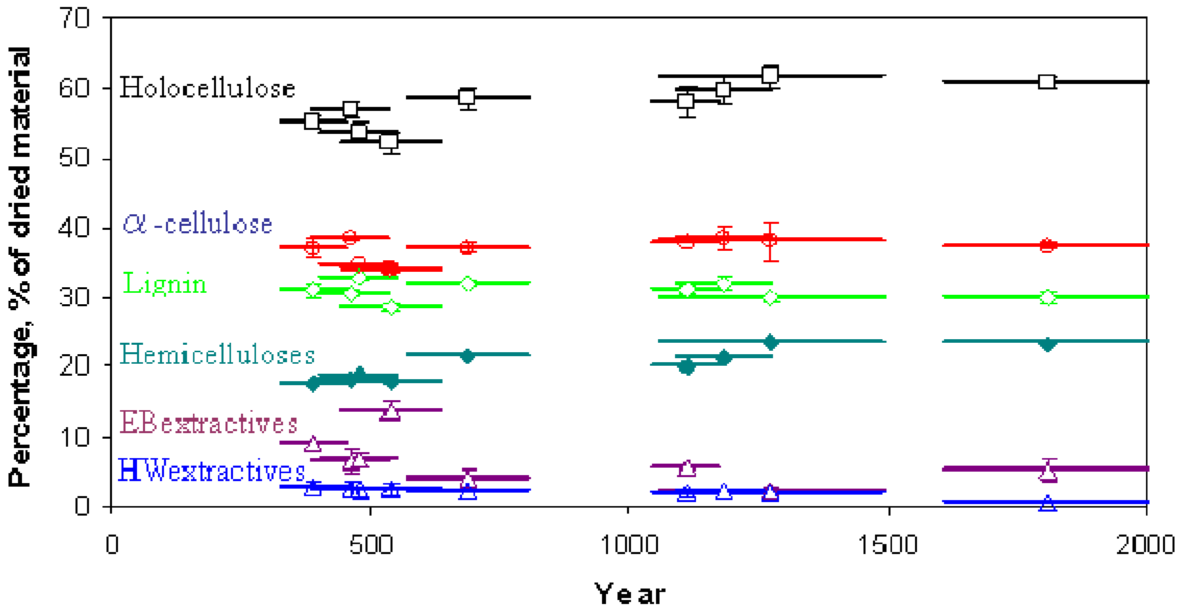

Fig.3 Relationships between chemical content and age [8]

Application for the restoration of wooden Buddhist sculpture

Hinoki (*Chamaecyparis obtusa*) specimens were subjected to the heat treatment 180℃, 150℃, 120℃ and 90℃ respectively under various treatment time by normal oven method. An accelerated aging test was performed by heat treatment to obtain different levels of accelerated aging wood samples. A comparison will be made between mechanical and chemical properties of naturally aged wood and that of heat-treated wood [Matsuo, M., et al, pending]. These results can be used as the standards in comparison with the actual naturally aged wood materials for application for the restoration of wooden artefacts.

Fig.4 is an example of an application of this basic research for the restoration of a Japanese Buddhist sculpture made from hinoki (*Chamaecyparis obtusa* Endl). These Rahotsu, curled hair on the Buddhist head, was missing before restoration [Fig.4 (a)] and some new wooden curled hairs were made by the restorer, Mr. Kenichiro Yano. Before using the wood for restoration, the wooden curled hair was subjected to heat treatment to adjust to the condition suitable for the restoration of the Buddhist sculpture. Fig.4 (b) shows the wooden curled hairs in an antique-like finish following heat accelerated aging.

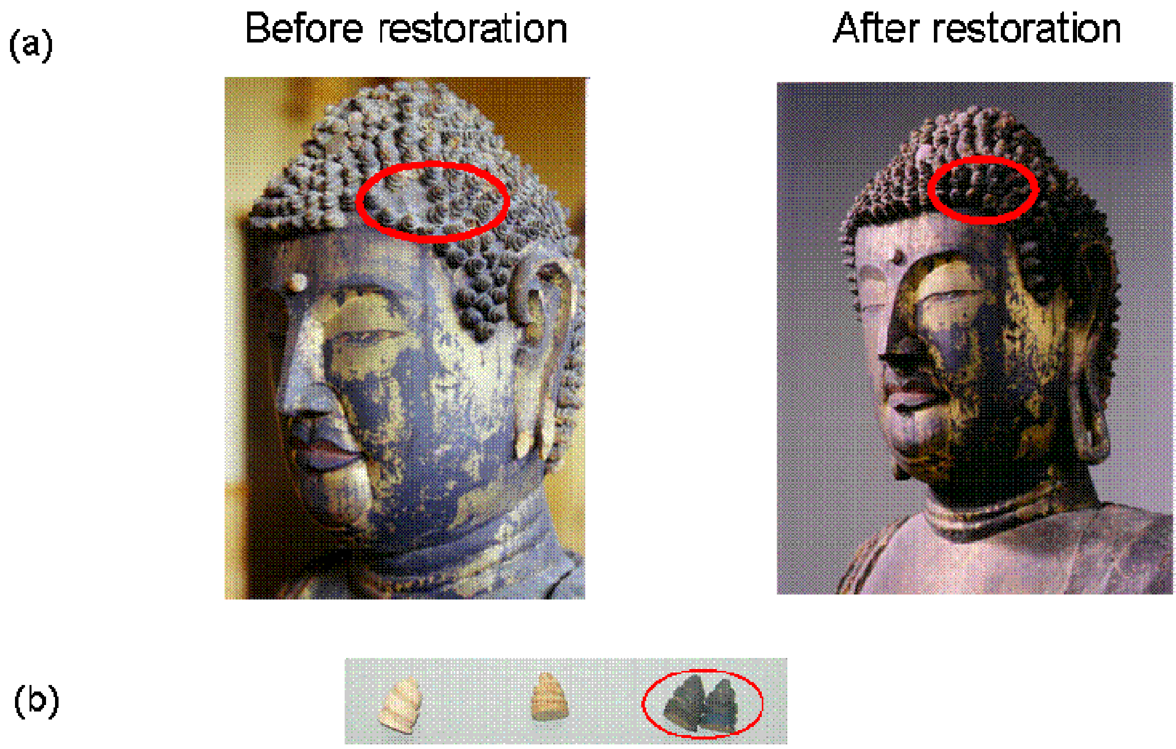

Fig.4 An application for the restoration of a Japanese Buddhist sculpture.
(a) "Yakushinyorai" of Okubodera temple built in the 8th century. This Buddhist sculpture was restored by Mr. Kenichiro Yano.
(b) Wooden curled hair after accelerated aging treatment, prepared to replace a loss.
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Conclusions

As a practical consequence, the results obtained suggest that ancient wood can be considered safe as long as it is not subject to unusual action perpendicular to the grain. The existence of large wooden structures dating back more than 1200 years is the clearest confirmation of that statement.

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