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Wood and Wood-Based Materials as Sensors—A Review of the Piezoelectric Effect in Wood

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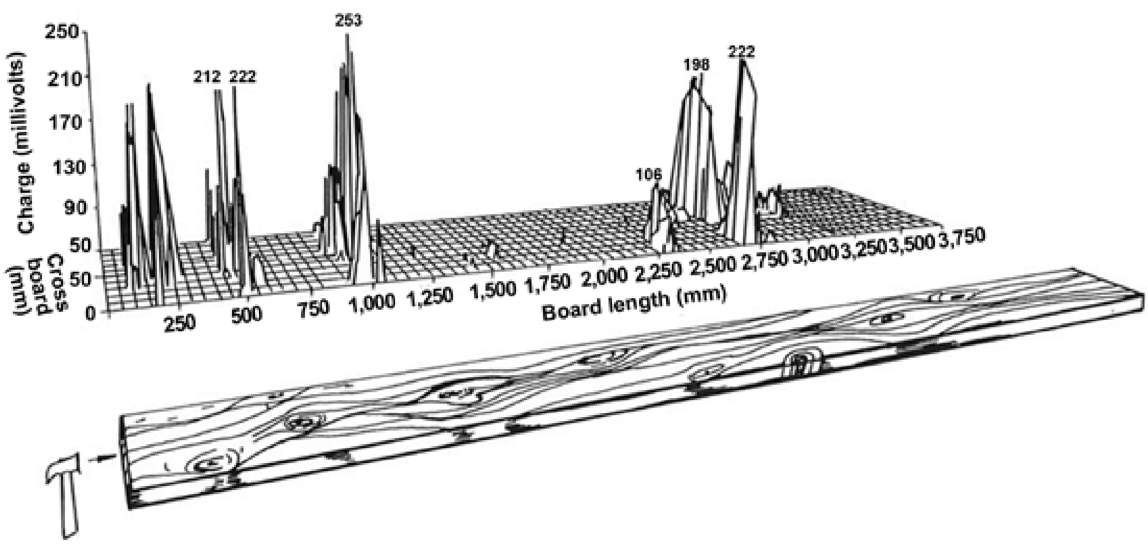

Abstract

A variety of techniques have been investigated for use in assessing the physical and mechanical properties of wood products and structures. Ultrasound, transverse vibration, and stress-wave based methods are all techniques that have shown promise for many nondestructive evaluation applications. These techniques and others rely on the use of measurement systems to monitor the response of the specimen under test. The primary sensing element in many widely used measurement systems uses piezoelectric sensors to monitor the response of the specimen under test to an external force. Commonly used piezoelectric sensors rely on a quartz crystal that converts mechanical energy into electrical energy. The electrical signal obtained from such sensors is then used in a variety of signal processing steps to arrive at basic properties of the material or structural system being tested.

The objective of the research presented in this paper was to examine the worldwide literature on the piezoelectric effect in wood. Results of a search of the worldwide literature, including a patent search, are presented and discussed.

Keywords: Crystallinity, defects, piezoelectric effect, piezoelectric modulus, wood

Contents

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Wood and Wood-Based Materials as Sensors—A Review of the Piezoelectric Effect in Wood

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Introduction

The USDA Forest Products Laboratory (FPL) is investigating various methods and technologies to address issues surrounding energy usage in wood structures. Investigations on the use of various insulation methodologies and other energy saving techniques are ongoing. One of the areas proposed for investigation is the concept of capturing, or harvesting, mechanical energy generated by appliances and occupants as they live and work in wood structures. A significant amount of research has been conducted to investigate energy harvesting for a wide range of applications—from harvesting energy from the boots of soldiers to power their portable electronic field equipment to using harvesting technologies to provide power for in-service sensors for monitoring transportation structures. The key component in these harvesting systems is a primary sensing element that converts mechanical energy into electrical energy. Such elements are composed of natural or man-made piezoelectric materials.

Although wood is a complex biological material, it has been shown experimentally that wood exhibits a distinguishable piezoelectric effect. We conducted a worldwide literature review to examine the piezoelectric effect in wood. The goals of our review were to 1. Examine the worldwide literature on the piezoelectric effect in wood, and 2. Summarize results of the main findings reported in the literature. The objective of this paper is to present the results of our review.

Approach

To review the state-of-the-art in the piezoelectric effect in wood, an extensive literature search on the piezoelectric effect in wood was conducted using CAB Abstracts. CAB Abstracts is an applied life sciences bibliographic database emphasizing agricultural literature that is international in scope. The database covers international issues in agricultural, forestry, and allied disciplines in the life sciences from 150 countries in 50 languages. It includes English abstracts for most articles. Our review of abstracts covered the years from 1939 to 2010 and consisted of three searches of abstracts using three different sets of word descriptors. The first search required that the word "wood" was used and the word "piezo" could be anywhere in the records. This search yielded 12 records. Our second search of the abstracts used "wood" in the descriptor field and phrase "electrical properties" anywhere in the records. 334 records were discovered, of which 196 were selected for applicability. The third search we conducted used "wood" in the descriptor field and the truncation "piezo" anywhere in the records. Based on these results and several additional sources, 31 technical documents and 4 patents were selected for intensive review.

Technical Documents Reviewed in a Chronological Order

1. Shubnikov 1946
2. Bazhenov 1950
3. Fukada 1955
4. Fukada and others 1957
5. Bazhenov 1961
6. Galligan and Bertholf 1963
7. Fukada, E. 1965
8. Galligan and Courteau 1965
9. Kytmanov 1967
10. Lin, R.T. 1967
11. Fukada 1968
12. Hirai and others 1968a

13. Hirai and others 1968b
14. Hirai and others 1970
15. Hirai and others 1972
16. Maeda and others 1977
17. Hirai and Yamaguchi 1979
18. Kellog 1981
19. Pizzi and Eaton 1984
20. Knuffel and Pizzi 1986
21. Fei and Zeng 1987
22. Knuffel 1988
23. Hirai and others 1992
24. Suzuki and others 1992
25. Hirai and others 1993
26. Nakai and Takemura 1993
27. Suzuki and Hirai 1995
28. Nakai and others 1998
29. Smittakorn and Heyliger 2001
30. Suzuki and others 2003
31. Nakai and others 2005

Patents Selected for Review

1. Best 1935
2. Sanders 2001
3. Lammer 2006
4. Churchill and Arms 2010

Research Summary

Table 1 presents a summary of several of the significant findings in chronological order from the technical papers we reviewed. Note that a piezoelectric effect in wood was first hypothesized, and later discovered, by Russian scientists in the 1940s–50s. Their work was initiated in an effort to find an appropriate trigger mechanism for military equipment, specifically missiles. Since then, research has been conducted to explore relationships between fundamental wood characteristics and the piezoelectric effect observed.

Table 1—Significant findings in a chronological order

Year	Author	Reported findings
1946	Shubnikov	Discovery of piezo-effect in wood
1950	Bazhenov and Konstantinova	First reported experiments on piezoelectricity in wood
1955	Fukada	Inverse piezoelectric effect in wood
1963	Galligan and Bertholf	Use of piezoelectric textures to observe stress wave behavior in wood
1970	Hirai and others	Effects of tree growth, wood quality, degree of crystallinity, and micellar orientation
1984	Pizzi and Eaton	Correlation between molecular forces in cellulose I crystal and piezoelectric effect
1993	Nakai and Takemura	Species, grain orientation effects
1998	Nakai and others	Relationship to static and vibration properties
2005	Nakai and others	Relationship to crystal lattice strain and tension stress of individual wood fibers

Discussion

Fundamental Concepts

Piezoelectricity is the charge that accumulates in certain solid materials (notably crystals, certain ceramics, and biological matter such as bone and various proteins) in response to applied mechanical stress. Piezoelectricity means electricity resulting from pressure and is the direct result of the piezoelectric effect.

The piezoelectric effect is understood as the linear electromechanical interaction between mechanical and electrical state in crystalline materials. Piezoelectric effect is a reversible process in that materials exhibiting direct piezoelectric effect (the internal generation of electrical charge resulting from an applied mechanical force) also exhibit the reverse piezoelectric effect (internal generation of a mechanical strain resulting from an applied electrical field). For example, lead zirconate titanate crystals will generate measurable piezoelectricity when their static structure is deformed by about 0.1% of the original dimension. Conversely, those same crystals will change about 0.1% of their static dimension when an external electric field is applied to the material.

Piezoelectricity is found in useful applications such as the production and detection of sound, generation of high voltages, electronic frequency generation, microbalances, and ultrafine focusing of optical assemblies.

The electrical character of a piezoelectric material must be that of a dielectric wherein charge displacement far outweighs conduction. Thus, the material behaves according to the relationship: $C = Q/V$, where C is the capacitance (farads); Q the charge (coulombs); and V, the potential difference (volts).

At the molecular level, a further requirement is placed on the piezoelectric material; there must be planes of molecular symmetry and within these planes the molecular constituents must be oriented in such a manner that the electrical charge centers are not symmetrically located. Monocrystals are representative of materials that meet these requirements.

When a piezoelectric crystal is strained, the charge centers are displaced relative to one another, causing a net charge to occur on the crystal surface. The dielectric nature of the crystal, obeying the capacitance relationship, permits the charge to appear as a voltage. This voltage is the electrical evidence of the piezoelectric effect.

The fundamental equations that describe the relationship between mechanical stress and electrical charge are the following:

$$P = dS + \eta E$$
$$\gamma = JS + dE$$

where a stress S is given to a substance, a polarization P is produced.

At the same time, an electric field E is also caused by the polarization of the substance. The coefficient d is called the piezoelectric modulus and η the electric susceptibility. The converse effect is shown by the second equation. A mechanical strain γ is produced by an applied electric field E and is accompanied by a stress S. The coefficient d for the converse effect is the same as that for the direct effect. If the condition is made that $E = 0$, then, by an experimental procedure, the modulus d can be determined as a ratio of polarization P to stress S. Thus relations between electrical polarization and mechanical stress are generally given the following equations:

$$P_x = d_{11}S_x + d_{12}S_y + d_{13}S_z + d_{14}S_{xy} + d_{15}S_{yz} + d_{16}S_{zx}$$
$$P_y = d_{21}S_x + d_{22}S_y + d_{23}S_z + d_{24}S_{xy} + d_{25}S_{yz} + d_{26}S_{zx}$$
$$P_z = d_{31}S_x + d_{32}S_y + d_{33}S_z + d_{34}S_{xy} + d_{35}S_{yz} + d_{36}S_{zx}$$

Where P_x, P_y, P_z represent the polarizations in xx, yy, and zz-directions, S_{yz}, S_{zx}, and S_{xy} represent the shear stress in *yz*, *zx*, and *xy* planes, respectively. The piezoelectric modulus d_{ij} relates each component of the polarization to each component of stress. In general, there are 18 components of d_{ij} and they are represented by a piezoelectric tensor as follows:

$$\begin{matrix} d_{11} & d_{12} & d_{13} & d_{14} & d_{15} & d_{16} \\ d_{21} & d_{22} & d_{23} & d_{24} & d_{25} & d_{26} \\ d_{31} & d_{32} & d_{33} & d_{34} & d_{35} & d_{36} \end{matrix}$$

By examination of the geometrical relationship between applied stress and the resulting polarization in wood, the piezoelectric tensor for wood has been determined as follows:

$$\begin{matrix} 0 & 0 & 0 & d_{14} & 0 & 0 \\ 0 & 0 & 0 & 0 & d_{25} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{matrix}$$

The modulus d_{14} means that shear stress in the *yz* plane produces polarization in the *x*-direction, and the modulus d_{25} means that shear stress in the *zx* plane produces polarization in the *y*-direction. Experimentally, their magnitudes are nearly the same and their sign is opposite. This fact makes evident that the piezoelectric effect is symmetrical about the *z*-axis.

Characteristics of piezoelectricity considered above apply directly to monocrystalline materials. Piezoelectricity of wood cannot be discussed easily in this context; while the same fundamental relations are believed applicable, it is necessary to consider the extremely heterogeneous nature of wood. Shubnikov (1946) noted this fact in some of the first reported work on piezoelectricity of wood; he proposed the concept of “piezoelectric texture” to represent a system consisting of many crystalline particles oriented unidirectionally.

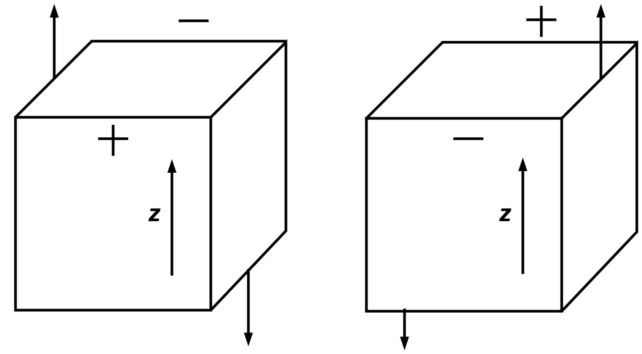

Figure 1—General scheme to produce piezoelectric polarization in wood (Fukada 1968). Graphic used by permission of Washington State University, Pullman.

The piezoelectric effect in wood may be observed as illustrated in Figure 1. The z-axis represents the fiber direction in wood. If a shearing stress is applied as indicated by arrows, an electrical polarization takes place in the direction perpendicular to the plane of the stress. The sign of the value of polarization is reversed when the direction of shear is reversed.

Rectangular coordinates are assigned to the wood structure with the *z*, *x*, and *y* axes representing the longitudinal, radial, and tangential directions in a tree trunk, respectively (Fig. 2).

It is known that cellulose is crystallized to a fairly large extent and that the unit cell of cellulose crystal belongs to monoclinic symmetry C_2. The piezoelectric tensor for a crystal is determined by the symmetry of a crystal lattice (Fukada 1968).

The tensor for a crystal with the symmetry C_2 is

$$\begin{matrix} 0 & 0 & 0 & d_{14} & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & d_{25} & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & d_{36} \end{matrix}$$

where the zz-axis is taken in the direction of the longitudinal axis of the molecules in the crystal. Eight components of the piezoelectric modulus should be finite.

The structure of wood composed of cellulose fiber is very complicated. Assume that the fiber is composed of many numbers of cellulose crystallites, orientated in the same direction, is the fiber axis, and that such fibers are regularly orientated parallel to the trunk axis. Figure 3 illustrates the uniaxial orientation of cellulose crystallites. The positive

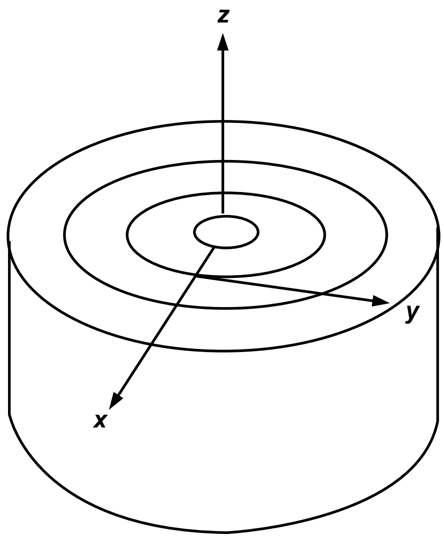

Figure 2—Rectangular coordinates assigned to wood (Fukada 1968). Graphic used by permission of Washington State University, Pullman.

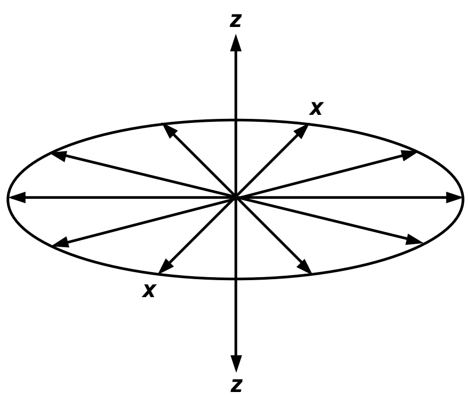

Figure 3—Uniaxial and non-polar orientation of crystallites (Fukada 1968). Graphic used by permission of the Journal of Wood Science and Technology.

end of the zz-axis of each crystallite is distributed at random in the axis of symmetry, that is, with the same probability for two opposite directions. The xx-axis of each crystallite is distributed at random and uniformly in the plane perpendicular to the axis of symmetry. The piezoelectric modulus for such an assembled system of crystallites can be calculated by taking an average of the moduli of the crystallites. Then it turns out that only d_{14} and d_{25} are finite for the system and that the other moduli become zero due to cancellation of the effect. The values of d_{14} and d_{25} of the system are proportional to the mean value of d_{14} and d_{25} in the single crystal of cellulose. The coefficient of proportion is dependent on density, crystallinity, and degree of orientation.

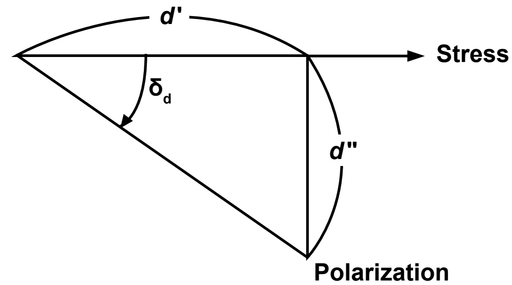

Figure 4—Vector representation of stress S and polarization P (Fukada 1968). Graphic used by permission of the Journal of Wood Science and Technology.

The piezoelectric tensor for such an assembly of unidirectionally orientated crystallites is

$$\begin{matrix} 0 & 0 & 0 & d_{14} & 0 & 0 \\ 0 & 0 & 0 & 0 & -d_{14} & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{matrix}$$

This tensor form is identical to that experimentally determined for wood.

Cellulose fibrils twist spirally with a certain angle to the longitudinal axis of the cell. However, if the average is taken for the layers in which fibrils describe a spiral form in alternative directions, the form of the resultant tensor of piezoelectric modulus is the same as derived above.

Since polymeric substances possess a viscoelastic property, it is anticipated that when stress is applied, electrical polarization does not appear instantly but arises gradually with time. Therefore, the piezoelectric modulus is treated as a complex quantity and determines the phase lag between stress and polarization as well as the absolute value of the modulus.

Figure 4 represents stress and polarization in a vector diagram. The polarization is delayed behind the stress by an angle δ_d. The component of polarization in phase with the stress represents the real part of modulus d' and the component of polarization 90º out of phase with the stress of the imaginary part of modulus d''. The ratio of d'' to d' may be expressed as the tangent of δ_d. These relationships are very similar to those encountered with the complex mechanical compliance and the complex dielectric constant.

Baseline Studies

Table 2 provides a summary of the species used in several reported studies. Note that a wide range of species has been used in these studies, and all have exhibited a piezoelectric effect. Reported moisture content values of the specimens used in the studies varied considerably; from a relatively dry state (below 10%) to over 70%. The specimens used were relatively small, with any dimension not exceeding 60 mm. Galligan and Courteau (1965), Knuffel (1988), and Knuffel and Pizzi (1986) were exceptions—they used lumber size specimens in their experiments.

Table 2—A list of wood species investigated for piezoelectric effect in previous studies

Reference	Species
Fei and Zeng 1987	*Magnolia grandiflora* Linn *Tilia amurensis* Rupr *Taxodium* ascendens Brongn *Pinus massoniana* Lamb *Cunninghamia lanceolata* Hook
Fukada and others 1957	(10 old timbers from 8 years to 1,300 years)
Galligan and Courteau 1965	Douglas-fir
Hirai and others 1968	Tsuga (*Tsuga sieboldii* Carr.) Shioji (*Fraxinus mandshurica* Rupr.) Shirakaba (*Betula platyphylla* SUKATCHEV. var.; *japonica* HARA.) Hônoki (*Magnolia obovata* THUNB) Taiwanhinoki (*Chamaecyparis taiwanensis* MASAM. et SUZUKI) Kiri (*Paulownia tomentosa* STEUD.) Hinoki (*Chamaecyparis obtuse* ENDL.) Sugi (*Cryptomeria japonica* D. DON) Konara (*Quercus serrata* MURRAY.) Akamatsu I (*Pinus densiflora* SIEB. et ZUCC.) Akamatsu II Douglas-fir (*Pseudotsuga taxifolia* BRITT.) Makanba
Hirai and others 1970	Sugi (summerwood and springwood)
Hirai and others 1972	Hinoki tree (*Chamaecyparis obtuse* SIEB. et ZUCC)
Hirai and Yamaguchi 1979	Hinoki
Knuffel and Pizzi 1986	*Pinus patula*
Knuffel 1988	*Pinus patula* *P. taeda* *P. elliottii*
Maeda and others 1977	Japanese cedar
Nakai and Takemura 1993	Beisugi (*Thuja plicata* Donn) Hinoki (*Chamaecyparis obtuse* ((S. and Z.)) Endl.) Beitsuga (*Tsuga heterophylla* ((Raf.)) Sarg.) Beimatsu (*Pseudotsuga menziesii* ((Mirb.)) Franco) Buna (*Fagus crenata* Bl.)
Nakai and others 1998	Sitka spruce (*Picea sitchensis* Carr.)
Nakai and others 2005	Japanese cypress (*Chamaecyparis obtuse* Endl.)
Suzuki and others 1992	Hinoki (*Chamaecyparis obtuse* ((S. and Z.)) Endl.) Beimatsu (*Pseudotsuga menziesii* ((Mirb.)) Franco) Beihiba (*Chamaecyparis nootkatensis* ((D. Don)) Spach) Agathis (*Agathis* sp.) Igem (*Podocarpus imbricatus* Bl.) Momi (*Abies firm* S. and Z.) White fir (*Abies alba* Mill.) Spruce (*Picea pungens* Engelm) Shinanoki (*Tilia japonica* Simk) Katsura (*Cercidiphyllum japonicum* S. and Z.) Buna (*Fagus crenata* Bl.) Lauan (*Pentacme contorta* Merr. and Rolfe) Nato (*Palaquium* sp.) Matoa (*Pometia pinnata* Forst.) Sugar maple (*Acer saccharum* Marsh.)
Suzuki and Hirai 1995	*Chamaecyparis botusa* Endlicher *Larix leptolepis* Gordon *Magnolia ovobata* Thunberg

Most reported work used test setups that resulted in a uniform compressive stress being applied to the specimen, orienting each specimen so that the angle between growth rings and the application of load was approximately 45º. The electric charge generated was detected by electrodes that consisted of conductive paint, glued-on metal foil, pins, or small metal buttons placed against a specimen's surface.

Based on early experimentation by Bazhenov (1961), Fukuda (1955, 1965), and Hirai and others (1970), the magnitude of the piezoelectric modulus of wood is approximately 1/20 of that of a quartz crystal. Bazhenov (1961) and Hirai and others (1970) found that the values of the piezoelectric modulus, d_{14}, increased gradually from the pith to the bark of a tree. They also reported that the values of the piezoelectric modulus for springwood and summerwood, for the same year's growth, were nearly equal.

Fukada and others (1957) found that the piezoelectric moduli increased with increasing density. Bazhenov (1961) found that the piezoelectric modulus d_{25} increased and that of d_{14} decreased with increasing density in pines. Hirai and others (1968a) confirmed that the d_{25} piezoelectric modulus increased with increasing density, but they show no data for d_{14}.

Bazhenov (1961) found that the piezoelectric modulus is related to temperature, and it increases as temperature increases. Maeda and others (1977) found that d' of the piezoelectric constant of the Japanese cedar at 74% of moisture content increased with the increasing temperature for the piezoelectric constant determined at 10 Hz.

Smittakorn and Heyliger (2001) developed a theoretical model for the steady-state and transient behavior of adaptive wood composite plates composed of layers of wood and other piezoelectric materials to simultaneously study the effects of mechanical, electrical, temperature, and moisture fields. They considered the theoretical model as a means of studying any laminated wood plate where the elastic, temperature, moisture, and electric fields influence the overall structural response. Their results of studying a representative example provided an indication of the level of response of adaptive wood composites, although no experimental verification had been conducted in their investigation.

Origin of the Piezoelectric Effect in Wood

Fukada (1955) and Bazhenov (1961) both hypothesized that the piezoelectric effect observed in wood originates in crystalline cellulose regions of the wood cell wall and that its intensity is dependent upon the degree of crystallinity. Hirai and others (1970) furthered that hypothesis, postulating that the magnitude of the piezoelectric modulus of wood depend upon degree of crystallinity and orientation of cellulose crystals in the cell wall.

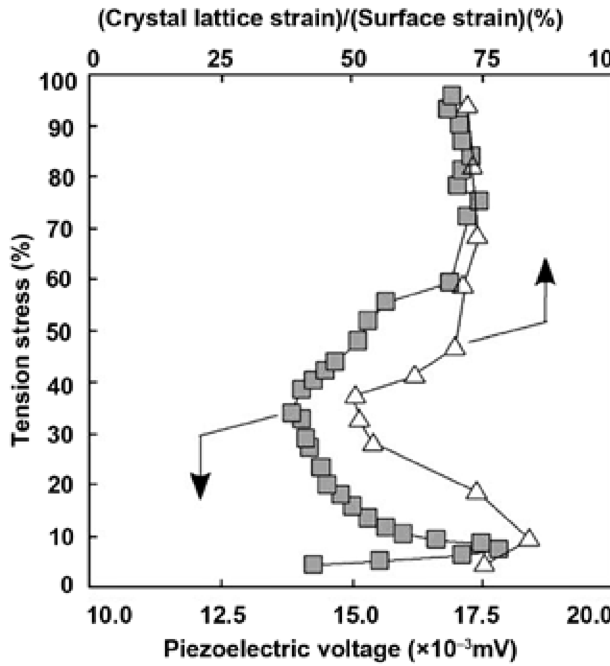

Figure 5—Relationships between the ratios of crystal lattice strain to surface strain (triangles), piezoelectric voltage (squares), and tension stress. Note: values of tension stress are shown as a percentage of ultimate tensile stress (Nakai and others 2005). Graphic used by permission of the Journal of Wood Science and Technology.

Using conformational analysis, Pizzi and Eaton (1984) concluded that van der Waal forces were responsible for the piezoelectric effect in wood. They concluded that the electrical charge most likely develops in response to an imposed shear force that results in laminar lateral–longitudinal deformations in the five-strand unit of the crystalline cellulose I molecule found in the microfibrils of wood. They also concluded that electrostatic and hydrogen bond interactions do not contribute to the piezoelectric effect.

Hirai and others (1968b, 1972) have shown that the piezoelectric modulus can be increased by increasing the crystallinity of the cellulose by treatment with gamma rays, exposure to high temperature for extended periods, liquid ammonia, ethlyenediamine, or sodium hydroxide. Fukada and others (1957) found that aging wood increased its crystallinity and its piezoelectric modulus. Based on his experimental results, he also postulated that fungal decomposition decreased both crystallinity and piezoelectric modulus.

Nakai and others (2005) found that the first and second peaks in the piezoelectric voltage appeared almost simultaneously with the peak of the ratio of crystal lattice strain to surface strain (Fig. 5). They also noted that the piezoelectric response decreased because of the effect of microscopic cracks in their specimens.

Piezoelectric Effect and the Properties of Wood and Wood Structural Members

Nakai and others (1998) measured the piezoelectricity of kiln-dried Sitka spruce specimens and simultaneously recorded scanning electron microscope images in real time to observe the deformation process of wood. Results of their experiments showed that there were two types of microscopic destruction in the specimens. With the first type, although a small uprush around the boundary of the annual ring was observed, the specimens were broken only by shearing fracture in the 45º direction. With the second type, the specimens were finally broken by shearing fracture after repeated buckling. They found that the piezoelectric voltage increased almost linearly in the elastic region, preceded to the maximal point, and then decreased gradually, and a clear peak appeared in the bucking and shearing fracture.

Nakai and Takemura (1993) measured the piezoelectricity of air-dried specimens (from five species) under time-varying load to investigate the possible relationship between piezoelectricity and the fracture of wood. A time-varying load was applied at a constant rate, accompanying a preliminary load and a sinusoidal load with a frequency of 20 Hz. They found that the greatest voltage of the piezoelectric signals as reported in a previous paper was in the case of a grain angle of 45º, and the voltages of the piezoelectric signals depended on the magnitude of the load, species, and grain angle. The results of their experiments showed that the piezoelectricity–time curves can be classified into three types (Type A, B, and C). Each curve consists of an initial rising part, a gradually increasing part, a subsequent decreasing part, and finally, a rapid rising and falling (Type A and B) or merely falling part (Type C), where the second part of the Type B is much flatter compared with that of the Type A. They also found that decreasing piezoelectricity against an increasing load was another characteristic behavior in the plastic region before a sudden fracture of a specimen.

Fukada and others (1957) found that the relation between the dynamic Young's modulus and the piezoelectric constant of the old timbers was linear (Fig. 6). Nakai and others (1998) reported a similar linear relation in the kiln-dried Sitka spruce with the exact relationship between the dynamic Young's modulus and the piezoelectric constant as

$$E_c\ (\times 10^3\ \text{kgf/cm}^2) = 1.18\left(\frac{P_\text{p}}{\rho \times L_\text{p}}\right) + 3.15$$

Hirai and others (1968a) found that the piezoelectric effect varied with the angle between the direction of the stress and the direction of the fiber axis and that maximum piezoelectric polarization was obtained when the direction of the stresses were at angles of 45º and 135º with the direction of the fiber axis (Fig. 7).

Knuffel and Pizzi (1986) measured the piezoelectric effect in *Pinus patula* structural timber beams. They found that the piezoelectric signal usually began smaller, increased to maximum after about five cycles, and then began to attenuate to zero. Also, the piezoelectric response started to develop almost simultaneously with the arrival of the stress wave and reached its first peak within 0.0001 s. They observed that the first peak of the piezoelectric signals might be either positive or negative, which are uncontaminated by resonance. They also found that the piezoelectric effect in the wet boards was still found to be very strong. But because of the conductive conditions, the electrical signal originating at the beginning of the board propagated faster than the stress wave, and at 20% moisture content, the piezoelectric effect began to coincide with the arrival of the stress wave.

Knuffel (1988) investigated the effect of the natural defects on the piezoelectric effect in structural timber. There were

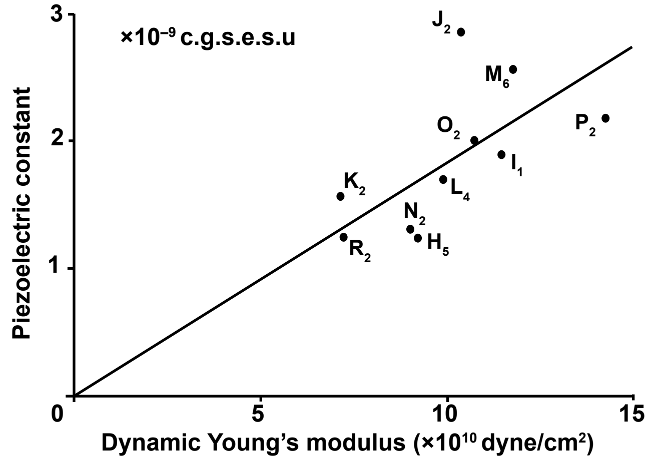

Figure 6—The relation between dynamic Young's modulus and the piezoelectric constants of old timbers (Fukada and others 1957). Graphic used by permission of Oyo Buturi.

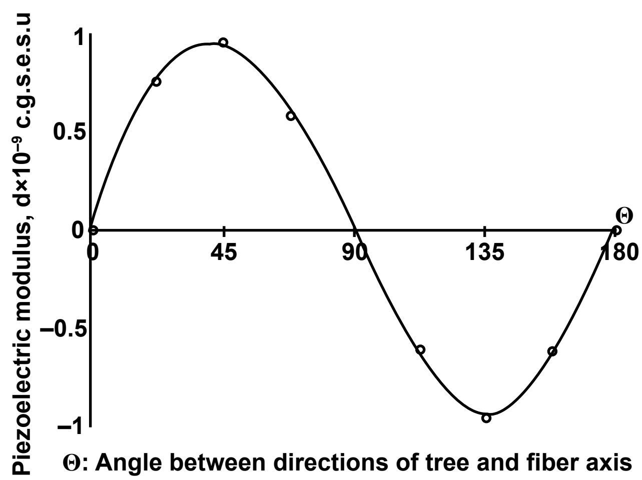

Figure 7—Anisotropy of piezoelectric modulus (Hirai and others 1968). Graphic used by permission of Washington State University, Pullman.

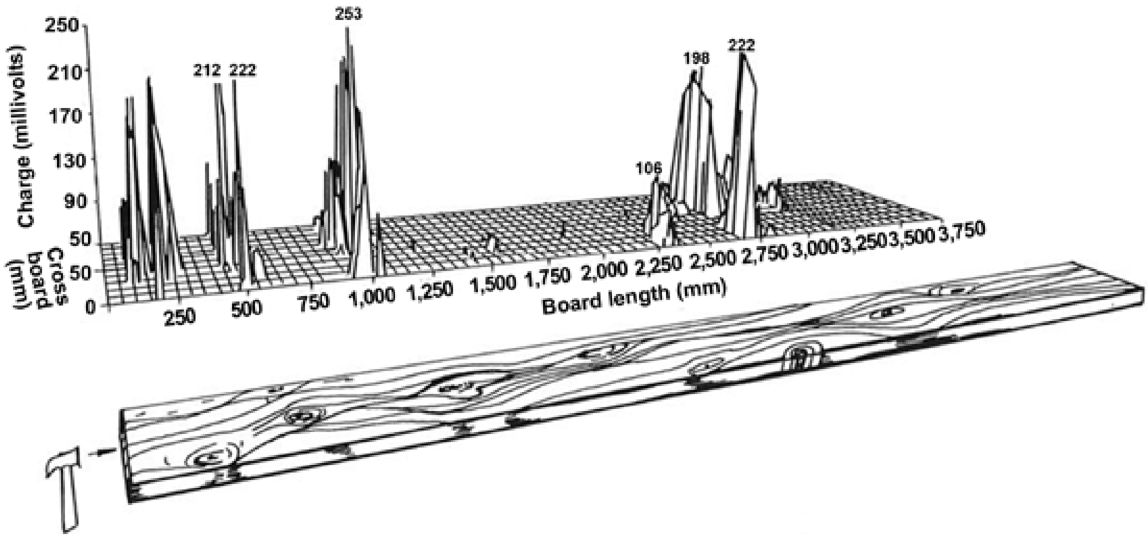

Figure 8—Piezoelectric response in structural timber (Knuffel 1988). Graphic used by permission of *Holzforschung.*

three findings from their investigation. Firstly, the piezoelectric first wavepeak values showed a definite and very sensitive increase in amplitude in the vicinity of knots and cross-grain (Fig. 8). Second, the piezoelectric response was far more sensitive to the defects than to MOE. At last, the piezoelectric effect was directly related to strain concentrations in the anatomical structure.

Summary

1. Research has been conducted on the piezoelectric effect in wood and wood materials, starting as early as the 1940s.
2. A number of wood species have been shown to exhibit a piezoelectric effect.
3. The magnitude of the piezoelectric modulus of wood is approximately 1/20 of that of a quartz crystal.
4. Several studies have been conducted to identify the origin of the piezoelectric effect in wood.
5. Studies have been conducted to explore its potential for evaluating the structural properties of wood structural members.

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