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IEEE Trial-Use Design Guide for Wood Transmission Structures

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Abstract: IEEE Std 751, IEEE Trial-Use Design Guide for Wood Transmission Structures, discusses the structural design and application of wood transmission structures. The guide includes definitions, application of loads, structure application, characteristics of natural wood and laminated wood members, design stresses, fabrication of laminated wood members, connections, nonwood members, erection and framing, and quality assurance.

Keywords: overhead transmission lines, wood transmission structures

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Foreword

(This Foreword is not a part of IEEE Std 751, IEEE Trial-Use Design Guide for Wood Transmission Structures.)

This guide was written using United States material references and measurements. The engineering concepts presented may be applied to the material and measurement system of any country. The guide has been prepared using input from design engineers, manufacturers, and the research and testing communities. We are especially grateful for information and input received from the following organizations: Electric Power Research Institute (EPRI), United States Department of Agriculture (USDA) Forest Products Lab, and American Wood-Preserver's Institute (AWPI).

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IEEE Trial-Use Design Guide for Wood Transmission Structures

1. Introduction

1.1 Scope

The purpose of this design guide is to provide the design engineer with methods for the design of wood structures for overhead electric transmission lines.

Wood is one of the most common structural materials used in the United States and Canada for high-voltage transmission structures, especially in the 69 kV through 345 kV range. To date there has been limited guidance to the design engineer on how to approach the design of transmission structures using wood as a structural material. This guide consolidates useful information, methods, and reference materials that define the state-of-the-art in the design of wood pole transmission structures into one document.

The guide is intended to serve a purpose similar to that of the American Society of Civil Engineers (ASCE) *Guide for Design of Steel Transmission Towers* [43]¹, and *Design of Steel Transmission Pole Structures* [37]. Like these documents, this guide is meant to provide the design engineer with good engineering design practices. Legislated requirements, such as the National Electrical Safety Code (ANSI C2-1990 [5]), should be used in conjunction with this document.

The guide covers application of wood in transmission structures, characteristics of wood and recommended stresses, methods of analysis, loadings, laminated material, connections, nonwood members, erection and framing, quality assurance, electrical considerations, and testing of wood structures.

The guide discusses both deterministic and probabilistic (reliability-based) design procedures. In both cases, the guide utilizes the load and resistance factor design (LRFD) format. The LRFD approach can be summarized by the following formula:

(Resistance Side) (Load-Effect Side)

$$\phi R_n \geq \gamma_o \sum_{i=1}^n \gamma_i Q_i \quad (\text{Eq 1.1})$$

¹The numbers in brackets correspond to those of the references in A1.1.

ϕ is the resistance factor or strength-reduction factor. ϕ is usually less than 1 and is discussed in detail in Section 5, Structural Analysis and Design.

R_n is the nominal resistance of the material used. Recommended values for R_n are found in Section 3, Characteristics of Wood.

γ_o is an analysis factor that accounts for inaccuracies associated with the structural analysis and is greater than or equal to 1. A discussion of recommended adjustments to the load side of this formula is found in Section 5.

The summation in Eq 1.1 represents all loads Q_i that act on the line simultaneously. γ_i is the load factor (greater than or equal to 1) to adjust the loads to account for uncertainties. This relationship is discussed in [24] through [26], [28], and [29].

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⁸This publication can be obtained from the American Plywood Association, P.O. Box 11700, Tacoma, WA 98411.

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¹²NFPA publications can be obtained from the National Forest Products Association, 1250 Connecticut Ave. NW, Washington, DC, 20036.

¹³REA publications can be obtained from the Rural Electrification Administration, Publications, 12th and Independence Ave., Washington, DC 20250.

¹⁴SPIB publications can be obtained from the Southern Pine Inspection Bureau, 4709 Scenic Hwy., Pensacola, FL 32504.

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1.3. Definitions

1.3.1 General

The reader should be aware of the terms *distribution line*, *transmission line*, and *line* as used throughout this design guide. A *distribution line* is usually considered to be a radial line of lower voltage; a *transmission line* is usually considered to be a line of higher voltage that connects substations together; and the term *line* may refer to either. The design engineer should determine which are appropriate for each particular application. Note that the term *overhead ground wire* is used in this document; it is also known as *overhead shield wire* or *overhead static wire*. These terms are equal.

1.3.2 Glossary of Terms

anisotropic: Of unequal physical properties along different axes.

bearing plates: Plates of large surface area attached to the structure below ground surface to prevent uplift or to increase the bearing capability in unstable soils.

bog anchor: A heavy anchor of large surface area for use in unstable soils.

bog shoe: A piece of material, such as a section of pole or railroad tie, attached horizontally below the ground surface to increase the bearing area in unstable soils. Usually four shoes are installed, one on each side of the pole, at ninety degrees to each other.

bole: The main stem of a tree of substantial diameter. Roughly capable of yielding sawn timber, veneer logs, or poles.

bonding: The electrical interconnecting of conductive parts, designed to maintain a common electrical potential.

bunker material: Expendable material used for protecting commodities during shipping or hauling.

cambium: A layer of delicate meristematic tissue between the inner bark and the wood that produces all secondary growth in plants and is responsible for the annual rings of wood.

cant hook: A tool similar to a peavey (except that it has a blunt end) used to turn a pole or stabilize it if necessary during installation.

check: (1) A separation along the grain of the wood, the separation occurring across the annual rings (AWPA Std M5-77, included in [32]), and (2) A lengthwise separation of the wood that usually extends across the rings of annual growth and commonly results from stresses set up in wood during seasoning (*Wood Handbook* [64]).

¹⁶WCLIB publications can be obtained from the West Coast Inspection Bureau, P.O. Box 23145, Portland, OR 97223.

cross-grained wood: Wood in which the fibers deviate from a line parallel to the sides of the piece. Cross-grain may be either diagonal or spiral grain or a combination of the two (*Wood Handbook* [64]).

dap: To cut and form a recess in timbers for making a joint.

davit arm: A rigid upswept cantilever arm used to support an insulator string.

distribution line: Electric power lines that distribute power from a main source sub-station to consumers, usually at a voltage of 34.5 kV or less.

dunnage material: See bunker material.

gaff: Tool used to handle and roll poles. *Also:* gaff hook.

gain: Flat surface cut into side of pole to facilitate connections. Also a connection device to accomplish the same purpose without cutting the pole.

isokeraunic map: A map showing equal levels of thunderstorm activity. Usually shown in mean annual days of thunderstorm activity. *Also:* isoceraunic. *See:* **keraunic level**.

keraunic level: Number of thunderstorm days in a given area for a specified period of time. *Also:* ceraunic. *See:* **isokeraunic map**.

layup: The preparation of wood strips for gluing together.

plane of contraflexure: The plane of contraflexure in an H-frame structure locates the inflection points for each pole. An inflection point is a point in the pole that separates an outward pole curvature from an inward pole curvature. This is also a location of zero moment.

rake: An inclination from the perpendicular.

raptor: A bird of prey.

resistance-reduction factor: A number usually less than or equal to 1 used in LRFD. Called strength-reduction factor in this guide.

rock socket: A hole drilled in good rock for installing either expanding or grouted guy anchors.

ultimate strength: The rated breaking strength of a material determined by the results of tests to destruction.

undressed timber: Rough unsurfaced lumber.

unsupported length: Unbraced length of a column (see Fig 1).

uplift plates: *See:* **bearing plates**.

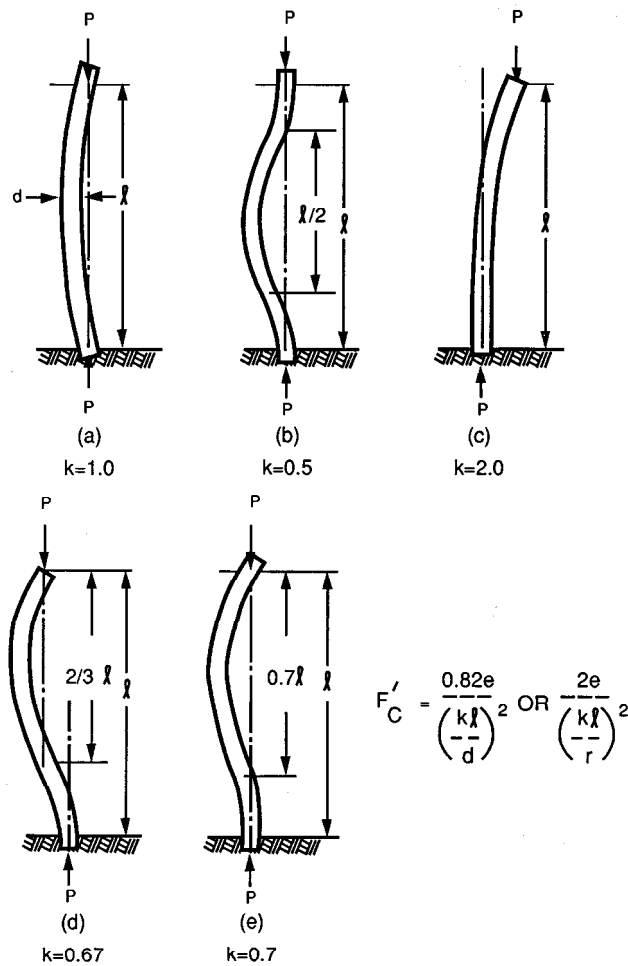


Figure 1 — Effective Length Factors, k

1.3.3. List of Abbreviations

AITC	American Institute of Timber Construction
AMORGL	Adjusted Modulus of Rupture at the Ground Line
ANSI	American National Standards Institute
ASCE	American Society of Civil Engineers
ASTM	American Society for Testing and Materials
AWPA	American Wood-Preserver's Association
AWPI	American Wood-Preserver's Institute
DF	Douglas Fir
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
NDS	National Design Specification (see NFPA T901 [50])
NEC	National Electric Code
NESC	National Electrical Safety Code
OSHA	Occupational Safety and Health Administration
PS	Product Standard
REA	Rural Electrification Administration
SPIB	Southern Pine Inspection Bureau
SYP	Southern Yellow Pine
USDA	United States Department of Agriculture
WCLIB	West Coast Lumber Inspection Bureau

2. Structure Application

2.1 General

Wood is a highly versatile structural material that has been used extensively in transmission lines at voltages up to and including 345 kV. Wood structures may be composed of undressed timber for poles or crossarms, sawn timber for crossarms and braces, and laminated members for a range of applications.

2.2 Wood Benefits

The extensive use of wood in North America for transmission lines is primarily due to economics. It may be more economical to build a transmission line of wood than to build a line using other materials for voltages of 345 kV and below. In addition to its cost-effectiveness, wood has other benefits that should be considered by a design engineer. Some of these benefits include the following:

- 1) *Design Benefits.* Wood structures provide flexible mechanical systems. The effect of impact and vibration loads on the structure are reduced because of the high energy-absorption characteristics of wood. The design engineer may select wood because it is readily available. The lead time for replacement of structures that fail under unexpected loads can be extremely short. Wood structures have been used as temporary replacement structures for lines at 500 and 765 kV because of their availability.
- 2) *Construction Benefits.* Although certain precautions must be taken in the erection of a wood structure, construction crews find wood to be easy to handle. Holes can be field-drilled in the poles to accommodate assembly. Most structures can be assembled on the ground and lifted into place. Foundation preparation is usually simple and inexpensive.

- 3) *Environmental and Aesthetic Considerations.* The use of wood need not deplete natural resources because wood, if properly managed, is a renewable resource. A wood transmission line may be more acceptable than a line built of another material to today's environmentally aware public. A transmission line using wood structures generally has a low profile, and the color of a natural or stained wood structure allows it to blend in with its surroundings.

2.3 Wood Limitations

Wood as a structural material has certain limitations of which the design engineer should be aware. Some limitations can be eliminated by utilizing wood structure systems composed of laminated members, which can be custom-fabricated for the application required. Some of the design limitations include the following:

- 1) *Variability of Properties.* The strength and stiffness properties of wood will vary because wood is biological in origin. Wood is anisotropic with differing properties in the longitudinal, radial, and transverse directions.
- 2) *Strength Limitations.* Strength is governed by the physical properties of the species of trees available for structures. The strength of wood transmission structures can be increased and variability decreased by using laminated members. Increased strength is accomplished mainly by increasing the physical dimensions of the structural member. Pole classes greater than H-6 are generally not readily available at the heights required for transmission structures. If large quantities of very heavy class poles are required to meet strength requirements, the design engineer may wish to evaluate alternative designs such as laminated or nonwood structures. Crossarm capacity can be increased by the use of hanger bracing, knee bracing, double crossarms, spar arms (poles), or laminated or nonwood crossarms.
- 3) *Strain Limitation.* A consideration associated with wood is its tendency to acquire a permanent set (creep) when subjected to a constant load. Permanent set can reduce structural capacity, decrease clearances, or become visually objectionable.
- 4) *Maintenance Considerations.* The strength and cross section of wood deteriorates with time. This should be accounted for in the original design. Continuous and carefully planned maintenance programs are a necessity.
- 5) *Guying Requirements.* The guying of wood structures is used primarily to resist conductor and overhead ground wire tension loads at angles and dead ends. Guying is sometimes needed to increase transverse or longitudinal structure strength and to prevent pole uplift and reduced deflections at road crossings. Land-use restrictions that reduce the available guy lead may preclude the use of guys and require the designer to use a nonwood structure.
- 6) *Terrain Requirements.* Severe side slopes restrict the use of wood structures at guyed structure locations where the side slope will not permit installation of guys and anchors. Areas where poor soil conditions occur may preclude the use of direct embedment of wood poles and may require the need for special foundations and/or nonwood structures. Some structural design considerations used to overcome soil restrictions include bog shoes, swamp cradles, and uplift plates.

3. Characteristics of Wood

3.1 Physical Characteristics

There are more than 180 species of trees grown in North America that may be considered commercially important. However, the number suitable for structural purposes is relatively small. Nineteen distinct species have published mechanical properties (see [24] through [26] and [56]); these are ash, beech, birch, cedar, chestnut, cypress, elm, fir, gum, hemlock, hickory, larch, maple, oak, pecan, pine, poplar, redwood, spruce, and tupelo. Of these, three species have the size, durability (when treated), and the availability necessary to be used for transmission structures. These are the southern pine group, which grow in the Atlantic and Gulf

States, and as far north as West Virginia and Kentucky; western red cedar; and Coastal Douglas fir (Inland Douglas fir is not recommended by AWP for transmission structures), which grow in the coastal region of Washington, Oregon, California, and British Columbia.

It is not necessary for the engineer to know a great deal about the chemical composition of wood in using any species in the design of transmission structures. More important to the design engineer are the mechanical properties and the factors affecting their strength and stiffness.

3.1.1 Directional Properties

Wood has different mechanical properties with respect to its three principal axes because of the orientation of wood cells and the manner in which a tree grows. These axes, shown in Fig 2, are longitudinal (A_l), radial (A_r), and tangential (A_t).

The differences among properties in the radial and tangential directions are seldom of practical importance in most structural designs; it is usually sufficient to differentiate only between properties that are parallel and those that are perpendicular to the grain. Parallel to grain is along the longitudinal axis, and perpendicular to grain is on the radial and tangential axes.

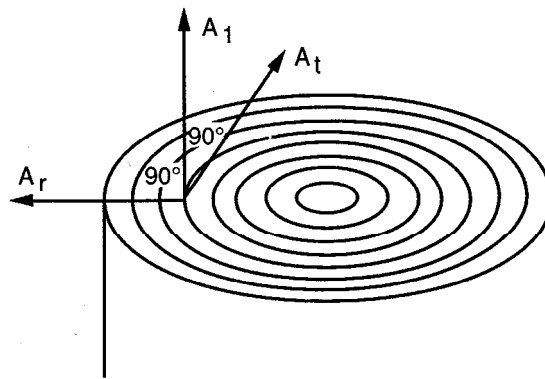


Figure 2 — The Three Principal Axes of Wood

3.1.2 Growth Rings

The concentric rings, as shown in Fig 2, start at the center or pith of the tree and continue outward toward the bark. Each ring represents the growth of the tree during one growth period. Growth is in the cambium (layer just inside the bark) and tends to push the bark outward. It is possible to distinguish one growth ring from another when trees grow in a variable climate, because the cells formed late in the growing season are different from those formed early in the growing season.

3.1.3 Earlywood and Latewood

Each growth ring is divided into two layers. The inner one, called earlywood (spring wood), is developed during the first part of the growing season. It is composed of large cells with thin walls and is usually lighter in color than latewood. The outer layer, called latewood (summer wood), consists of smaller cells with thicker walls and is the darker portion of the annual ring. It is heavier and stronger than earlywood and has an important effect upon the strength properties. Earlywood and latewood differ significantly in their preservative treatment properties.

3.1.4 Density

Density of a particular piece of wood is influenced by the rate of tree growth and the amount of latewood present. This means that the strength of a piece of clear wood is dependent on the amount and distribution of the cell walls throughout the cross section.

The number of growth rings per inch radially and the proportion of latewood in the cross section are considered as part of the specification when grading lumber and are part of the specification in ANSI O5.1-1987 [9]. Material having the specified minimum number of rings per inch is termed *close-grained*, and material that has in addition one third or more of latewood is termed *dense*.

3.1.5 Slope of Grain

Where the fibers of a wood member are not parallel to the edge of the piece, cross grain exists and the longitudinal tensile and compressive stress have components acting across the grain. Wood is weakest across the grain, and therefore, limits to the amount of slope of cross grain have been set. The slope of grain is expressed as a ratio between a one-inch deviation of the grain from the side of the piece and the distance within which this deviation occurs. Figure 3 illustrates a 1:12 slope of grain in a crossarm.

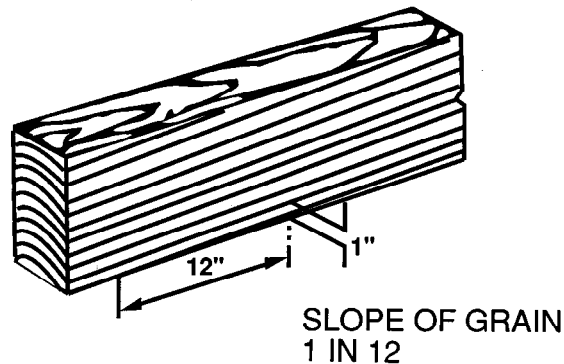


Figure 3 — Measurement of Slope of Grain

When the fibers in wood poles are not parallel with the sides of the pole but twist around the pole, the condition is called spiral grain. Spiral grain is limited as specified by ANSI O5.1-1987 [9].

3.1.6 Knots

Knots are the remains of branches in the trunk or bole of a tree. There are many types and classifications of knots, depending on the appearance of the knot on a sawn surface and whether or not the fibers of the knot are intergrown with the tree trunk. A knot on the face of a sawn surface is merely a section of the entire knot, and its shape depends on the direction in which it is cut. Round, oval, or spike knots are possible. The knot is classed as intergrown when the limb of the tree is alive when it is cut. However, if the limb dies and the trunk continues to grow, the dead limb will be enclosed, which means that the fibers of the knot and the trunk are discontinuous. The result is called an encased knot and often these knots become loose during seasoning.

The occurrence of knots in a structural member does not necessarily mean that the piece will not give adequate performance. Knots do affect the strength because it is necessary for the grain to deviate from its regular direction in passing around them and because of the checking that may occur in and around them during seasoning. The weakening effect is greater when the sawn piece is in tension rather than compression, and the influence on bending strength is dependent on the location of the knot and the area it occupies in the cross section.

Knot limitations for utility poles are set by the West Coast Lumber Inspection Bureau (see [63]), American Lumber Standards, ANSI O5.1-1987 [9], and the Southern Pine Inspection Bureau (see [55]).

3.1.7 Moisture Content

A tree develops in the presence of moisture and throughout its life it is moist or “green.” The amount of moisture in a live tree varies among species, in individual trees, and in different parts of the same tree.

Moisture Content (MC) is the weight of the water contained in wood, expressed as a percentage of the weight of the oven-dry wood. An oven-dry condition is reached when no further loss of weight is experienced in oven drying. As wood loses moisture, there is a point where the water in the cell cavity has evaporated but the cell wall is still saturated. This is known as the Fiber Saturation Point (FSP). FSP occurs at approximately 27 to 30% MC (this can vary significantly with different species). As the MC is reduced below the FSP, shrinkage occurs at significantly different rates along the different axis. Also, the strength and stiffness increase with reduction in MC.

Wood gives off or takes on moisture from the surrounding atmosphere with change in temperature and relative humidity until it attains a balance relative to the ambient conditions. The MC at this point is known as the Equilibrium Moisture Content (EMC). Before preservative treatment (except creosote), the MC of wood must be brought below the fiber saturation point. Wood is brought below the FSP to provide space for preservative in the wood, and to eliminate favorable growth conditions for fungi. Wood is also brought to the EMC to further reduce checking.

Because of the extreme difficulty of drying large wood members, only the surface area of a pole will usually be near EMC. In service, as the pole dries, the surface dries faster than the interior and shrinks more, resulting in checks. These checks often allow fungi to enter the pole in later years.

3.1.8 Heartwood and Sapwood

The central portion of the trunk and branches of a tree that surrounds the pith is called the heartwood. It consists entirely of inactive tissue. The sapwood, the portion of the trunk between the heartwood and the bark, contains some living cells. All wood is formed as sapwood, and, as the tree continues to grow, the inner portion gradually becomes heartwood. Usually, the heartwood is darker in color than the sapwood, but in some species there is little difference between them. The heartwoods of the southern pines and Douglas fir are not stronger than the sapwoods, but the heartwoods are more resistant to decay. The heartwood of many species, especially western red cedar, contains extractives that make it decay resistant.

3.1.9 Decay

Unless wood is given preservative treatment or unless it contains a high percentage of naturally durable heartwood, it will decay. Cycles of wetting and drying encourage the growth of wood-destroying fungi.

In the earliest, or incipient, stage of decay, the fungi spread through the untreated wood in all directions from the point of inoculation. During this state, there is no definite visible dissolution of the infected piece or measurable loss of density.

Once decay has progressed beyond the incipient stage to the intermediate stage, the outward appearance of the wood is more perceptibly altered. The cell walls are disintegrated and the wood undergoes marked changes in strength, color, texture, and continuity. Fruiting bodies may begin to grow on the surface in the late or advanced stage of decay, and the wood may become punky, soft and spongy, pitted, or crumbly.

3.1.10 Seasoning

Well-developed techniques have been established for removing the large amounts of moisture normally present in green wood. Seasoning is essentially a drying process that removes moisture and relieves residual stresses. The four most common seasoning methods are air seasoning, kiln drying, Boulton drying, and steaming.

The most common method of preparing green lumber and timber for treatment is to stack them out of doors with dry sticks between the layers and allow them to air season. Unseasoned wood that is exposed to the open air, but protected from rain, will gradually dry out until it comes into approximate equilibrium with the average relative humidity of the air. This process is very time consuming; therefore, air seasoning is often used in combination with artificial seasoning. In an attempt to sterilize the pole from decay, all air-seasoned poles should be conditioned at time of treating so that the pith center of the pole is heated for at least 2 h at a temperature of not less than 150 °F.

The kiln-drying process consists of placing green wood in a chamber. Temperature, humidity, and air flow in this chamber are controlled to reduce the moisture content of the material. This process greatly speeds up the drying time compared to air seasoning and produces more constant and reliable results.

The Boulton process places green or partially seasoned wood in the treating cylinder and submerges it in hot oil. The temperature is maintained while a vacuum is gradually applied. Since the boiling point of water is lower under a partial vacuum than at atmospheric pressure, drying can proceed rather rapidly even at temperatures below 212 °F. This method allows the user to condition wood for treatment at temperatures considerably below those required in the steaming-and-vacuum process. Boultonizing is used primarily for Douglas fir and is also used to sterilize air-seasoned wood.

In the steaming process, also known as sterilization, used primarily for southern pine, the green wood is steamed in a treating cylinder for several hours. A vacuum is immediately applied when the steaming is completed. During the steaming period, as the temperature of the outer surface of the wood approaches 212 °F and when the vacuum is applied, the water is forced out or evaporated. The steaming and vacuum usually reduce the moisture content of green wood and the heating assists greatly in getting the preservative to penetrate.

3.1.11 Incising

Incising consists of making shallow, slit-like holes in the surface of material to be treated. These holes allow deeper and more uniform preservative treatment. Incising should be as required to achieve the necessary retention and penetration.

3.1.12 Treating

Wood can be protected from the attack of decay fungi by applying selected chemicals as wood preservatives. Wood preservatives fall into two general classes: (1) oil-borne preservatives using creosote, pentachlorophenol, or copper or zinc naphthenate and (2) water-borne preservatives ACA, ACZA, and CCA. Treatment should be specified with reference to the applicable American Wood Preserver's Association (AWPA) Standard for technical specifications for the preservatives and standard retentions (see [32]).

Creosote was one of the first substances used for treatment of poles and railroad ties. Creosote is a complex mixture of hydrocarbons, distilled from coal tar. It is a time-tested effective preservative that is still widely used. Creosote has some objectionable characteristics, however — it has a strong odor, it stains wood a dark color, and creosote-treated wood cannot be painted. Creosote should conform to AWPA Std P1 [32].

Pentachlorophenol (penta) contains chlorinated phenols and should conform to AWPA Std P8 [32].

The hydrocarbon solvents for introduction of the preservative into the wood should meet the requirements of AWPA Std P9 [32], Types A, B, C, D, and E as follows:

- 1) *Type A.* The original heavy oils used as solvents have behavior and properties similar to those of creosote products. The major use has been in poles, where oil moves down the pole and out into the soil at the ground line. Creosote also has this characteristic.
- 2) *Type B.* This process uses Liquified Petroleum Gas (LPG) as the solvent for the penta. After the wood is treated, the excess solvent is drawn off, leaving penta in solid form in the wood. This wood is dry to the touch and can be painted or stained.
- 3) *Type C.* This process uses lighter oil solvents with greater evaporation, leaving the surface fairly dry and lighter in color.
- 4) *Type D.* Hydrocarbon Solvent.
- 5) *Type E.* Water.

The most commonly used water-borne treatments are Chromated Copper Arsenate (CCA) for southern pine, Ammonical Copper Zinc Arsenate (ACZA), and Ammonical Copper Arsenate (ACA) for Douglas fir. These treatments should conform to AWPA Std P5 [32].

Copper and Zinc Naphthenate are not under the restrictive-use provision issued by the Environmental Protection Agency for creosotes, penta, or water-borne arsenic combinations (see [39]).

Wood treated with water-borne preservatives is clean and paintable after seasoning. The flammability of wood treated with water-borne preservatives is less than that of wood freshly treated with an oil.

Corrosion of fasteners may be a problem if treating formulations containing constituents that may form ionizing compounds within the wood are used. These constituents will react with each other to form free ionic compounds on and below the surface of the pole and have been associated with some corrosion problems on metal hardware.

3.2 Mechanical Characteristics

3.2.1 Wood Poles

The major material properties of interest in the design of wood poles are bending strength and Modulus of Elasticity (MOE).

Recommended design strengths currently used for wood poles are specified in ANSI O5.1-1987 [9]. The strengths presented in ANSI O5.1-1987 are tabulated in Tables 3.1–3.4.

Table 3.1 — ANSI O5.1-1987 Designated Fiber Stress

Treatment Group	Genus and Species	Fiber Stress (psi)
Treatment Group A (air seasoned)		
Cedar, northern white (eastern)	<i>Thuja occidentalis</i>	4000
Spruce, Englemann*	<i>Picea englemannii</i>	5600
Cedar, western red	<i>Thuja plicata</i>	6000
Pine, ponderosa	<i>Pinus ponderosa</i>	6000
Fir, western (true fir)		6600
California red*	<i>Abies magnifica</i>	
Grand*	<i>Abies grandis</i>	
Noble*	<i>Abies procera</i>	
Pacific silver*	<i>Abies amabilis</i>	
White*	<i>Abies concolor</i>	
Pine, jack	<i>Pinus banksiana</i>	6600
Pine, lodgepole	<i>Pinus contorta</i>	6600
Pine, red (Norway)	<i>Pinus resinosa</i>	6600
Redwood*	<i>Sequoia sempervirens</i>	6600
Spruce, Sitka*	<i>Picea sitchensis</i>	6600
Spruce, white*	<i>Picea glauca</i>	6600
Cedar, Alaska yellow	<i>Chamaecyparis nootkatensis</i>	7400
Hemlock, western*	<i>Tsuga heterophylla</i>	7400
Douglas fir, interior north	<i>Pseudotsuga menziesii</i>	8000
Treatment Group B (Boulton drying)		
Douglas fir, coastal	<i>Pseudotsuga menziesii</i>	8000
Larch, western	<i>Larix occidentalis</i>	8400
Treatment Group C (steam conditioned)		
Pine, southern		8000
Loblolly	<i>Pinus taeda</i>	
Longleaf	<i>Pinus palustris</i>	
Shortleaf	<i>Pinus echinata</i>	
Slash	<i>Pinus elliotii</i>	
Treatment Group D (kiln drying)		
Cedar, western red	<i>Thuja plicata</i>	6000
Douglas fir, interior north	<i>Pseudotsuga menziesii</i>	8000
Douglas fir, coastal	<i>Pseudotsuga menziesii</i>	8000

Treatment Group	Genus and Species	Fiber Stress (psi)
Larch, western	<i>Larix occidentalis</i>	8400
Pine, jack	<i>Pinus banksiana</i>	6600
Pine, lodgepole	<i>Pinus contorta</i>	6600
Pine, ponderosa	<i>Pinus ponderosa</i>	6000
Pine, red	<i>Pinus resinosa</i>	6600
Pine, southern		
Loblolly	<i>Pinus taeda</i>	8000
Longleaf	<i>Pinus palustris</i>	8000
Shortleaf	<i>Pinus echinata</i>	8000

*Not in common use according to Wood Preservation Statistics, Forest Service, US Department of Agriculture, 1961.

Table 3.2—Ground-Line Strength and Stiffness Values for New, Green Poles Less Than 50 ft Long [(1), (2)]

Species	Sample Size	AMORGL (3) Mean (psi)	COV (4)	Sample Size	MOE (5) Mean (106 psi)	COV (4)
Northern white cedar	28	4 100	0.173	—	—	—
Western red cedar	387	6 310	0.204	268	1.59	0.224
Pacific silver fir	51	6 380	0.173	51	1.67	0.215
Douglas fir						
Coastal	118	9 620	0.135	39	3.35	0.194
Interior	99	8 020	0.179	—	—	—
Western hemlock	154	7 530	0.180	154	2.23	0.216
Western larch	48	10 000	0.127	48	2.94	0.190
Jack pine	189	7 300	0.190	—	—	—
Lodgepole pine	218	6 650	0.194	108	1.84	0.223
Red pine (6)	331	6 310	0.174	229	1.63	0.234
Southern pine (7)	143	10 190	0.169	67	2.68	0.201
White spruce	56	5 520	0.208	56	1.44	0.239

NOTES:

1—Data were adapted from ANSI O5.1-1987 [9] and are based on class minimum circumferences (rather than measured circumferences as provided in ANSI O5.1-1987) at the tip and at 6 ft from the butt and linear taper between these points.

2—Values must be adjusted using the appropriate factors from Table 3.4.

3—AMORGL = Adjusted Modulus of Rupture at the Ground Line.

4—COV = Coefficient of Variation.

5—MOE = Modulus of Elasticity.

6—ANSI O5.1-1987. Red pine data were supplemented with Canada Corporation and Michigan Utilities Association test results.

7—Longleaf, shortleaf, slash, and loblolly pines.

Table 3.3—Ground-Line Strength and Stiffness Values for New, Green Poles, 50 ft and Longer, Used in Unguyed, Single-Pole Structures Only [(1), (2)]

Species	Sample Size	AMORGL (3) Mean (psi)	COV (4)	MOE (5)	
				Mean (10^6 psi)	COV (4)
Southern pine (6)	120	8430	0.206	2.51	0.184
Douglas fir					
(Coastal)	165	7860	0.144	2.64	0.182
Western red cedar	100	5200	0.192	1.59	0.229

NOTES:

1—Data are based on class minimum circumferences at the tip and at 6 ft from the butt and linear taper between these points.

2—Values must be adjusted using the appropriate factors from Table 3.5. Height correction is not required for Table 3.3 AMORGL values.

3—AMORGL = Adjusted Modulus of Rupture at the Ground Line.

4—COV = Coefficient of Variation.

5—MOE = Modulus of Elasticity.

6—Longleaf, shortleaf, slash, and loblolly pines.

Table 3.4—Ground-Line Strength and Stiffness Values for New, Green Poles, 50 ft and Longer, Used in Structures Other Than Unguyed Single-Pole Structures [(1), (2)]

Species	Sample Size	AMORGL (3) Mean (psi)	COV (4)	MOE (5)	
				Mean (10^6 psi)	COV (4)
Southern pine (6)	120	9400	0.125	2.51	0.184
Douglas fir					
(Coastal)	165	7860	0.144	2.64	0.182
Western red cedar	100	5200	0.192	1.59	0.229

NOTES:

1—Data are based on class minimum circumferences at the tip and at 6 ft from the butt and linear taper between these points.

2—Values must be adjusted using the appropriate factors from Tables 3.5 and 3.6.

3—AMORGL = Adjusted Modulus of Rupture at the Ground Line.

4—COV = Coefficient of Variation.

5—MOE = Modulus of Elasticity.

6—Longleaf, shortleaf, slash, and loblolly pines.

Current design practices require discussion of these methods for presenting strength characteristics for wood poles:

- 1) Deterministic
- 2) Probabilistic using ANSI O5.1-1987 pole dimensions
- 3) Probabilistic using actual pole dimensions

3.2.1.1 Deterministic Design.

Table 3.1 lists ANSI O5.1-1987 Designated Fiber Stress values for use in conjunction with design in accordance with the National Electrical Safety Code (ANSI C2-1990 [5]). This is a deterministic design approach with loads and strength specified by code.

Table 3.5—Correction Factors for Pole Strength and Stiffness AMORGL (1) and MOE (2)

Kiln Drying:	0.90
Boultonizing:	0.90–1 (3)
Steaming Conditioning: (Southern pine only)	0.85

NOTES:

1—AMORGL = Adjusted Modulus of Rupture at the Ground Line.

2—MOE = Modulus of Elasticity.

3—ASTM D2555-88e1 [13] suggests no correction factor required for boultonized Douglas fir poles.

3.2.1.2 Probabilistic Design Using ANSI O5.1-1987 Pole Dimensions.

Tables 3.2, 3.3, and 3.4 list Adjusted Modulus of Rupture at the Ground Line (AMORGL) values for use with probabilistic design methods. These values represent the average breaking strength in bending of actual wood pole samples adjusted to an equivalent breaking strength at the ground line as defined in ANSI O5.1-1987 [9] and for the minimum dimensions specified for each pole class in ANSI O5.1-1987. These values should be adjusted using appropriate ϕ values for treatment (Table 3.5), height (Table 3.6), exclusion limit, risk, age and decay, and other factors, which are discussed in Section 5.

Table 3.6—Height-Effect Correction Factors for AMORGL (1)

Species	Mean	COV (2)
Southern pine	$1-0.176h$ (3)	$1 + 2.072h$ (3)
Douglas fir	1	1
(Coastal)		
Western red cedar	1	1

NOTES:

1—AMORGL = Adjusted Modulus of Rupture at the Ground Line.

2—COV = Coefficient of Variation.

3— $h = X/L$ where X is the distance above ground line for which location of the AMORGL is computed, and L is the total above-ground length of the pole.

Table 3.7—Characteristics of Wood Crossarms

	Modulus of Rupture (psi)		Modulus of Elasticity (106 psi)		Compression Parallel to Grain (psi)	
	Mean	COV (1)	Mean	COV (1)	Mean	COV (1)
Douglas fir (2)	7540	0.160	1.613	0.220	3610	0.180
Southern yellow pine						
Grade 1 (3)	9020	0.240	1.145 (4)	0.231 (4)	5430	0.145
Southern yellow pine						
Grade 1 (3)	6510	0.316	1.145 (4)	0.265 (4)	4730	0.186

NOTES:

1—COV = Coefficient of Variation.

2—From [52].

3—From [39].

4—Average calculated from [52].

3.2.1.3 Probabilistic Design Using Actual Pole Dimensions

References [24] through [26] list values for Modulus of Rupture (MOR) for actual dimensions of wood pole species. These values should be used for applications in which actual pole dimensions are required, such as pole testing or evaluating the strength of in situ structures. The design engineer should adjust these values using appropriate ϕ values similar to those used in 3.2.1.2 above, when using MOR to evaluate the strength of existing structures for uprating. The design engineer should take special care in determining the age and decay factor of the pole. In place nondestructive testing or careful inspection of each structure should be used to evaluate the age and decay factor for uprating existing lines.

3.2.2 Crossarms and Braces.

Wood crossarms and braces for transmission structures are either Coastal Douglas fir or Southern yellow pine. Code values have not been published for transmission crossarm or wood brace design using either deterministic or probabilistic methods. Characteristics of concern for crossarms and braces are bending strength, MOE, and compression parallel to grain.

3.2.2.1 Deterministic Design.

It is recommended that a value of 7400 psi be used for crossarm and brace strength in bending for NESC loading conditions (see ANSI C2-1990 [5]).

3.2.2.2 Probabilistic Design.

Clear sample values are found in [13] and [52]. The values in Table 3.7 are suggested for use in probabilistic design. Corrections should be applied to these values in the same manner as for wood poles.

3.2.3 Modulus of Elasticity.

The MOE is a measure of stiffness. Table 3.8 lists recommended MOE values for deterministic design of wood poles and crossarms. Tables 3.2, 3.3, and 3.7 are used for probabilistic design.

Table 3.8—Modulus of Elasticity Values for Use in Deterministic Design

Pole Species	MOE* (106 psi)
Western larch	1.710
Southern yellow pine	1.800
Douglas fir	1.920
Lodgepole pine	1.340
Jack pine	1.220
Red (Norway) pine	1.800
Ponderosa pine	1.260
Western red cedar	1.120
Northern white cedar	0.800
Crossarm Species	
Douglas fir	1.920
Southern yellow pine	1.800

*.MOE = Modulus of Elasticity

4. Structure Loading

Loads to be applied in designing transmission line structures is an entire subject in itself, and has been covered in [44]. Users of this design guide should make themselves familiar with this publication.

Design engineers are further cautioned that there are legislated codes that specify structure loads. In the United States, the most familiar is the National Electrical Safety Code (NESC) (ANSI C2-1990 [5]). Several states have enacted codes that differ from the NESC, which may influence the final structure design.

5. Structural Analysis and Design

5.1 Introduction

5.1.1 General

Two design methods are discussed in this section: deterministic and probabilistic. The methods differ in how loads and strengths are determined. The methods of analysis presented can be applied to either design method. The most common wood transmission structures encountered are single-pole structures and H-frame structures with various crossarm, diagonal bracing, and guy configurations. This section describes procedures for analyzing and designing these structures.

5.1.2 Load Resistance Factor Design Format

The basic objectives of design are to provide a structure with resistance greater than the maximum load expected during the design lifetime, with the desired level of safety and reliability within acceptable economic parameters. This objective can be expressed in an LRFD format as

$$\phi R \geq \gamma Q \quad (\text{Eq 5.1})$$

R is a measure of resistance in this equation. The strength (capacity) factor, ϕ , is a multiplier usually less than or equal to 1, which limits R to account for the variability of the resistance property (strength, stiffness) considered. Q represents either a load or a load effect (stress, deflection) with the same units as R . γ is a load factor greater than or equal to 1 that compensates for uncertainty in the definition of loads and assumptions made in the analysis. The ϕ and γ factors, and the standard values of R and Q , are based on judgment, past practice, and on probabilistic studies.

5.1.3 Resistance and Load Values (R and Q)

For a wood pole designed in bending, R is the Adjusted Modulus of Rupture at the Ground Line (AMORGL), and Q is the calculated bending stress at the ground line for a given load (σ_g).

AMORGL is the calculated bending stress level at the ANSI O5.1-1987 [9] specified ground-line location and adjusted to the minimum dimensions specified in ANSI O5.1-1987. This value is determined at the failure load, regardless of where the failure occurred, and is not the actual stress at the point of failure on the measured circumferences of the pole. AMORGL values shown are valid only when designing new wood structures assuming minimum pole dimensions specified by ANSI O5.1-1987. The design engineer is cautioned that when analyzing a structure using actual pole dimensions, the values shown in Tables 3.2 and 3.4 of Section 3 should not be used (see [24] through [26]).

5.2 Deterministic Design

At the time of this guide's writing, most wood transmission structures in the United States are designed to National Electrical Safety Code (NESC) requirements (see ANSI C2-1990 [1]). Loads are developed using NESC overload capacity factors for designated loading areas for wind and ice loads and extreme wind loads. Strengths are defined as designated fiber stresses specified in Table 3.1. The designated fiber stress should be adjusted by the appropriate NESC strength factor.

Several states have their own design codes, which may vary considerably from the current edition of the NESC; for example, California uses CPUC-GO95 in place of the NESC.

5.3 Probabilistic Design

Probabilistic design incorporates constantly improved data on loading conditions and material properties, and results in design improvements that provide predictable reliability and possible economic benefits. The results obtained from probabilistic design concepts depend on the accuracy of the data base used. These data can accommodate local conditions. Current efforts to better define the probabilities of load occurrence, and properties of material, are necessary to improve design.

Load and material resistance factors reflect the desired level of reliability. They are determined from statistical studies of available data on loads and resistances, information on the performance of existing structures, probabilistic concepts, and importance and design life of the structure.

The accuracy of probabilistic design is improved as additional data are accumulated on the following:

- 1) Time-strength data, effects of treatment processes, moisture content, environment, service life, etc., on wood strength
- 2) Load occurrence and magnitude
- 3) Variabilities in analysis

5.3.1 Resistance and Load Factors (ϕ and γ)

Two methods are proposed for determining the resistance factor, ϕ , and load factor, γ .

5.3.1.1 Reliability Index Method

This method was developed by EPRI's Project 1352-2. Equations that determine resistance factors have been developed in [17] through [19], [28], and [29] and are shown below.

- 1) *Resistance (strength) factors*

$$\phi = e^{(-0.75\beta V)} \quad (\text{Eq 5.2})$$

where

- V = Coefficient of variation
 β = Reliability index

Coefficient of variations are provided for the following variables: material resistance, modulus of elasticity, maximum load for wind, ice, and wind in combination with ice.

- 2) *Load factors.* Corresponding load factors using the β reliability index are given in [28].

The design factor values thus depend upon the variabilities of the quantities involved and the overall reliability level desired, as indicated by the value of β , the reliability index. Higher reliability levels can be obtained by increasing the reliability index. The coefficients of variation and the mean values of the various quantities result from material and component testing and from load survey programs. The selected β value must be based upon successful past designs (a process called calibration) and other evidence of design adequacy. Studies to date indicate that a reasonable value to use for the reliability index β is in the range of 2 to 3.5.

5.3.1.2 Exclusion Limit — Return Period Method

This method is presented in the ASCE *Guidelines for Transmission Lines Structure Loading* [44]. It is similar to the method presented in several reports issued by the International Electrotechnical Commission (IEC) and is discussed in [42]. The method determines the load factor γ using a return period method, and the resistance factor ϕ using the exclusion limit concept. (The reliability index method discussed previously combines these factors into a reliability index β .)

5.3.1.2.1 Load Factor

Reference [44] provides a discussion of loads and load factors for transmission lines.

5.3.1.2.2 Resistance Factor

The design engineer should determine a reasonable lower exclusion limit for the particular service area of from 5 to 15% and apply this to an assumed normal distribution for wood poles and crossarms. This range of lower exclusion limits provides 95 to 85% probability that new poles and crossarms have actual strengths greater than the design strength.

The design strength should account for material-strength distribution, age, decay, conditioning method, and load duration.

- 1) *Material-Resistance Factor* (ϕ_1). The material-resistance factor is dependent on two variables — the coefficient of variation (COV) of the strength and the lower exclusion limit. The values derived from the Gaussian probability function are given in Table 5.1. This table assumes a normal distribution for strength. The lower exclusion limit is selected as explained above. The COV of strength is obtained from test data of the materials. Values of COV for round wood poles loaded in bending are given in Tables 3.2, 3.3, or 3.4. Table 3.7 gives the values for crossarms.
- 2) *Age and Decay Factor* (ϕ_2). Age and decay factors are dependent on the susceptibility to decay and on the maintenance program of the utility. A good pole maintenance program allows for a less conservative strength factor, whereas, a “replace ‘em when they break” program requires a more conservative factor (a lower ϕ value would be more conservative than a higher one).
- 3) *Conditioning Factor* (ϕ_3). Conditioning factors are available in Table 3.5.
- 4) *Load-Duration Factor* (ϕ_4). Wood properties were determined by tests with a typical load duration of 5 min. The strength properties predicted by 5-min tests must be modified to account for the time-dependent behavior of wood. When loads are applied for different periods, the load duration factors given in Table 5.2 are recommended.

Table 5.1 — Material-Resistance Factor (ϕ_1)

Lower Exclusion Limit (Risk of Not Meeting Design Strength Percent)	Coefficient of Variation of Strength (Percent)							
	5	7.5	10	15	30	25	30	35
Material-Resistance Factor (ϕ_1)								
2	0.90	0.85	0.80	0.69	0.59	0.49	0.39	0.28
5	0.92	0.88	0.84	0.75	0.67	0.59	0.51	0.43
10	0.94	0.90	0.87	0.81	0.74	0.68	0.62	0.55
15	0.95	0.92	0.90	0.84	0.79	0.74	0.69	0.64

5.3.2 Material Strength

Since wood is anisotropic, the engineer should use the appropriate fiber stresses for the relationship of applied load direction to the direction of the wood grain (see [65]). Mechanical properties at angle (Θ) to the grain (radial or tangential, see Fig 2) can be obtained by Hankinson's formula:

$$A_{\Theta} = \frac{A_t A_r}{A_t \sin^2 \Theta + A_r \cos^2 \Theta} \quad (\text{Eq 5.3})$$

where

- A_{Θ} = Property at an angle Θ from the fiber direction
- A_t = Property parallel to grain (longitudinal direction)
- A_r = Property perpendicular to grain (radial direction)

5.3.3 Example

An example to determine design strengths for a typical Southern Yellow Pine (SYP) steam-treated pole with wind loads follows:

- Assume a 15% lower exclusion limit and large transmission size poles. This means that 85% of the poles will have strength exceeding the lower exclusion limit.
- From Table 3.3, the mean AMORGL = 8430 psi, COV = 0.206,
- From Table 5.1, at risk = 15%, and COV = 20%, the material-resistance factor $\phi_1 = 0.79$,
- With a good maintenance program, the Age and Decay Factor $\phi_2 = 0.90$ ($\phi_2 = 0.70$ is recommended for utilities that have no pole maintenance program),
- From Table 3.5, for steam-treated poles $\phi_3 = 0.85$, and
- For a wind load, a load-duration factor $\phi_4 = 1$,
- The final allowable design strength is determined as

$$\phi_1 \phi_2 \phi_3 \phi_4 (8430) = 5095 \text{ psi} \quad (\text{Eq 5.4})$$

Table 5.2—Correction Factors for Wood Strength Based on Load Duration

Loading period	ϕ_4
Impact	1.25
Five minutes (test values and wind and construction or maintenance loads)	1.00
One day (ice)	0.80
Two months	0.70
Ten years	0.60
Dead load (permanent)	0.50

5.3.4 Probabilistic Design Analysis

The design formulas recommended in this guide use the design loads found in [44] and the allowable strengths determined in this guide.

The probability functions for load and strength are independent. Therefore, an exclusion limit of 10 or 15% will result in higher probability of withstand for a given line because the probability of having a combined event of low strength and high load occurring at any one structure simultaneously is lower than the probability of any event occurring independently.

The design engineer's judgment, based on past operating experience, importance of the line, the system's built-in redundancy, etc., determines a choice of exclusion limits and loads.

5.4 Analysis and Design of Single-Pole Structures

5.4.1 General

The main design consideration for most pole structures is to assure that the applied loads with appropriate overload factors do not exceed the designated fiber stresses with appropriate strength-reduction factors. For design engineers who do not have access to computer resources, the analysis procedure for single unguyed wood poles consists of idealizing the pole as a cantilever beam and computing stresses and deflections with elementary static formulas. Because this method neglects the vertical load stresses and nonlinear effects of secondary moments from deflections (P - Δ effect; see Fig 4), the computed response is lower than the actual value.

Structural analysis should consider the geometrically nonlinear P - Δ effect. However, the moment response is difficult to compute manually because the additional moment caused by the deflection causes additional deflection, which increases the moment. This iterative process is not practical to perform by hand. Recently developed computer programs perform this process and provide accurate results. Before computer methods are discussed, a hand method is described.

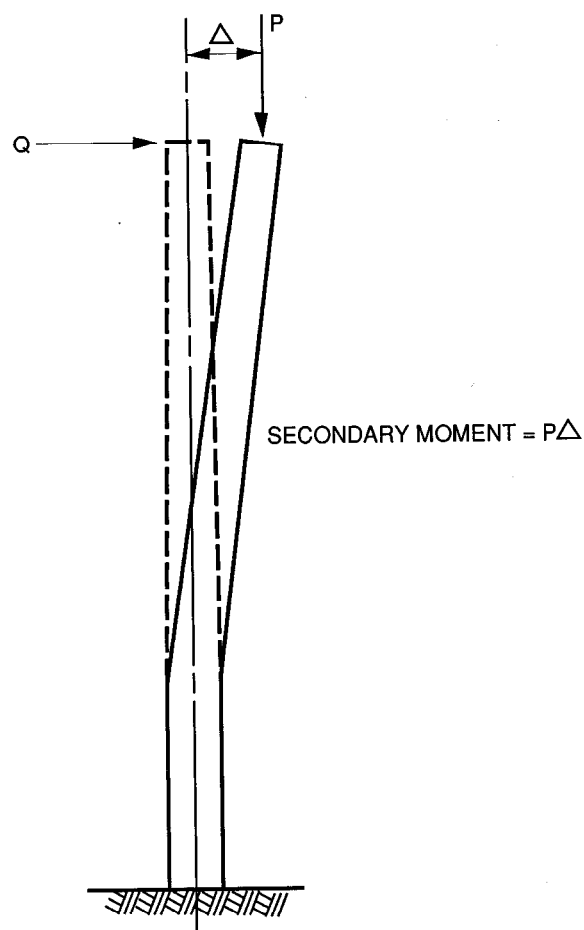


Figure 4 — P-Delta Effect

5.4.2 Resisting Moment

The basic strength formula is as follows:

$$f_b = \frac{M}{S} \quad (\text{Eq 5.5a})$$

where

- M = Resisting moment
- f_b = Maximum allowable fiber stress in bending
- S = Section modulus

For round solid timber sections in bending,

$$M = 0.0982 f_b d^3 \quad (\text{Eq 5.5b})$$

where d = Diameter.

Moment capacities are reduced at sections where bolt holes, notches, etc., exist (see [53] for details).

5.4.3 Primary Moment

The primary moment is $M = QL$, where Q is the resultant of the transverse loads on the overhead ground wire and phase wires, and L is the distance between the resultant load and the section considered. The moment due to the eccentric vertical load should be included if the conductors are arranged asymmetrically. Then

$$M = QL + Pe \quad (\text{Eq 5.5c})$$

where

P = Vertical load
 e = Eccentricity

5.4.4 Deflections and Secondary Moment

A secondary moment results from the lateral deflection of the pole at the load point relative to the point where the moment is calculated. The additional moment is equal to the vertical load P multiplied by the lateral deflection Δ . The secondary moment can be a significant percent of the total moment and should not be neglected. The deflection at Δ (the location of the resultant load) can be approximated by the equation

$$\Delta = \frac{6.79QL^3}{ed_g^3d_t} \frac{1}{1 - \frac{P}{P_{cr}}} \quad (\text{Eq 5.6})$$

where

Δ = Deflection in inches
 Q = Load in pounds
 L = Distance from the load to the section considered in inches
 e = Modulus of elasticity in psi
 d_g = Ground-line diameter in inches
 d_t = Diameter at load in inches
 P = Total vertical load in pounds
 P_{cr} = Critical buckling load in pounds

NOTE—Eq 5.6 contains a multiplication factor to increase deflection due to secondary moments.

The total vertical load is assumed to act at the same point as the resultant load Q . The pole is assumed to be plumb and fixed at the ground line. This assumption is non-conservative. The effects of movement below ground line (foundation movement) aggravate the P - Δ secondary moment, overall deflection, and wire clearances. Normally, this is not considered in design. The design engineer should consider foundation movement where large vertical wire loads or critical right-of-way clearances are encountered.

5.4.5 Location of Maximum Stress Point

The maximum stress for single unguyed poles supporting only lateral load seldom occurs at the ground line. Theoretically the maximum stress occurs where the diameter is 1.5 times the diameter at the point of load (see Fig 5). Because all data has been adjusted to the ground line for ANSI O.5-1987 pole dimensions, only stress at the ground line should be compared with AMORGL values. See the sample problem in the Appendix for analyzing a single-pole structure.