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ALLOWABLE STRESSES FOR THE UPSIDE-DOWN TIMBER INDUSTRY¹

Ronald W. Wolfe²

ABSTRACT

Round timbers have been used as foundation piling in North America for over 250 years, yet only in the last 50 years have concerns been raised about the need for allowable stresses for such timbers. Several organizations have published standards that govern the selection and derivation of working stress values for timber piles. This paper discusses the background for the ASTM derivations and factors to consider for improving model estimates of timber pile design stresses.

INTRODUCTION

Pile foundations constructed with round timbers have been used throughout the world for centuries. Timber piles have played a major role in the growth of the United States and have been used extensively in the construction of railroads and highways as well as locks and dams on navigable rivers. Prior to 1940, the relatively low cost and accessibility of timber in the United States encouraged overuse rather than efficient design of piles in foundation construction. By the 1950s, however, steel and concrete piling became more competitive and the timber piling industry began to take a serious interest in improving design efficiency.

Advantages of timber piles over steel and concrete include cost, availability, and natural taper. Timber piles, used in their natural form, require much lower production energy cost than competing materials. Pile-sized timbers are growing as a renewable resource in forests throughout the world. In most areas, these timber resources are more readily available than steel or concrete. The tapered shape of timber piles facilitates driving, serves to compact soil as the pile is driven, and provides a large butt end to absorb heavy driving energy and an adequate support for other construction members.

Disadvantages of timber piles include susceptibility to decay and marine borers and limitations on strength. In most areas, problems with decay and borer attack can be controlled with proper preservative treatment. Concerns about the strength of timber piles involve several factors that influence load capacity and location of the critical section. These factors include the reduction in section properties and clear wood strength from butt to tip of the pile, effects of naturally occurring imperfections, natural strength variability of wood, and effects of high temperature preconditioning for preservative treatment.

This paper provides a state of the art summary of the derivation of design stresses for timber piles. It focuses primarily on problems addressed in the development of currently accepted standards and provides commentary on areas of concern that require further research.

TIMBER PILE FOUNDATIONS

The type of foundation pile to be used for a given job is determined by the engineer on the basis of anticipated installation problems, support conditions, and cost. Timber piles are most often used in soils such as sand, clays and silt, where they can be easily driven and will be supported primarily by skin friction rather than end bearing. Although a timber pile may be supported by skin friction throughout its useful

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life, the pile-soil interaction is not well defined. As a result, for purposes of selecting pile size, timber piles are normally assumed to become end bearing in time.

Several factors may cause pile support conditions to shift from friction to end bearing. The three factors most often cited are a shift in the water table, down drag, and settlement caused by overloading. A change in soil saturation can lead to a critical change in confinement pressure as well as coefficient of friction between the soil and the pile. Down drag or “negative skin friction” occurs when piles installed in subsidence are subjected to downward forces resulting from soil strata along the pile that decrease in height relative to the pile. This force may drive the pile tip to heavy bearing or increase positive skin friction on sections of the pile below the down drag level. Finally, when a friction pile is loaded from above, stresses are greatest at the butt end until skin friction is exceeded. Once the skin friction is mobilized, the critical stress gradually moves down the pile to the point that any additional load is resisted totally by end bearing.

Group action or load sharing in a pile foundation is not accounted for in the derivation of pile design stresses. This phenomenon, which varies with site conditions and foundation configuration, cannot be generically applied to all piles used in a group. The decision to account for load sharing or to ignore it must be left to the foundation engineer.

CODES AND STANDARDS RELATING TO TIMBER PILES

When specifying timber piles, the three major concerns are quality, treatment, and strength. Each of these factors is considered separately in standards, which are developed to provide a common basis of understanding between pile producers and users. Pile quality includes size, straightness, and imperfections. Preservative treatment is important for piles that will be installed partially or totally above water. Pile strength affects drivability as well as foundation load capacity.

Standards Based on Quality

The first pile standards focused on acceptable dimensions and quality. Prior to 1940, the practice of driving enough piles to stabilize the soil and assuming that soil cohesion was the determining factor for foundation load capacity inspired little concern for pile strength. The primary concern was quality. One of the first standards relating to timber piles was the Specification for Round Timber Piles published by the American Society for Testing and Materials (ASTM) (4). This standard, designated ASTM D25, addresses pile quality. It was initially published as a tentative standard in 1915 but was accepted as a recognized standard for only 25 of the 40 years between 1915 and 1955. Over the past 30 years, this standard has undergone several revisions involving pile classification as well as pile size and quality. In 1970, ASTM D25 switched from a three-class system of specifying pile size and quality to a single set of quality criteria, which were slightly more liberal than those of the former class C piles. Along with a more liberal interpretation of allowable knot size, summarized in Table 1, the new pile classification system also permitted smaller timbers to be classified as piles. These changes were based on results of pile strength research, which led to the development of the ASTM standard on allowable stresses for timber piles.

Table 1 shows changes in ASTM D25 over time. The ASTM D25 standard includes pile classification, specifications for knots, and specifications for pile twist. For knot specifications, largest knots are classified by size and/or the ratio of knot diameter to pile diameter at location of knot; knot sum refers to sum of knot diameters per 0.3-m (1-ft) length of pile. Twist refers to pile grain angle slope per 6.1-m- (20-ft-) long section of pile.

Other organizations and building codes also have standards for specifying pile quality. The American Association of State Highway and Transportation Officials (AASHTO), standard M168-65 (2), and the American Railway Engineers Association (AREA) manual (Chapter 7, Part 1) (7) both have provisions traceable to the ASTM D25-37 standard. The American National Standards Institute (ANSI) (3) usually

Table 1. Evolution of ASTM D25 specification for round timber piles.

Year	ASTM D25 revision			
	1937	1958	1970	1986
Pile classification	A, B, C ^a	A, B, C	Friction and End Bearing	
Largest Sound Knot [% pile diameter (max. knot diameter)]	A and B For length ≤ 50 ft (15 m), 33% (10.2 cm (4 in.)) ^b For length >50 ft (15 m), 50% (12.7 cm (5 in.))	A and B Same as 1937 Same as 1937	50%	52%
	C NA	C 50% (12.7 cm (5 in.))		
Largest unsound knot	0	0 ^c	One-half size of largest sound knot	
Cluster knots	0	0	Same as largest sound knot	
Sum of knots in 1 in. (0.3 m) length of pile (% pile diameter)	NA	2 x largest sound knot	208%	104%
Twist (°/20 ft (6.1 m))	A and B 180° C 360°	A and B Same as 1937 C Same as 1937	180°	180°

^a Class A, suitable for use in heavy framed construction;
B, marine structures, building foundations, and general construction;
C, submerged foundations, cofferdams, falsework and light construction.

^b For class A and B piles >50 ft (15 m) long, the 1937 version allowed a 50% pile diameter knot, (maximum 5 in. (12.7 cm), anywhere along the pile; the 1958 revision limited this knot to within 25% of the pile length from the tip.

^c Unsound knots permitted for Southern Pine piles if knots <2 in. (5 cm) in diameter or one-sixth the pile diameter for class A and B piles and <2.5 in. (6.25 cm) or one-fourth the pile diameter for class C piles.

adopts the current ASTM D25 standard provisions. The building codes have their own standards for pile foundations but these normally reference a version of the ASTM standards for pile specifications and derivation of allowable stresses.

Standards Based on Preservative Treatment

The next group of standards to be developed dealt with preservative treatment. The most prominent of these were published by AASHTO, standard M133-73 (1), and the American Wood-Preservers' Association (AWPA), standard C3-88 (8). Today, the most commonly referenced standard for treatment of timber piles is AWPA C3-88. Included with treatment retention requirements for timber piles are steaming limitations. These are most critical for Southern Pine, which may be subjected to steaming temperatures as high as 118°C (245°F) for up to 15 h for fresh water piles and up to 20 h for marine piles. Douglas-fir is limited

to 115°C (240°F) for 6 h, and steaming is not permitted for oak. Conditioning temperatures may have a detrimental effect on wood strength (18) and should be accounted for when using treated timber piles.

Standards Based on Strength

When steel and concrete piles became accepted as alternative pile materials, with published strength values, users of timber piles were forced to respond with comparable values. The first user group to publish allowable stresses for timber piles was the American Association of State Highway Officials (AASHO) (now AASHTO). In 1941, the AASHO specifications gave timber pile allowable values of 8.28 MPa (1,200 lb/in²) for Douglas-fir, 7.59 MPa (1,100 lb/in²) for red oak, and 6.89 MPa (1,000 lb/in²) for Southern Pine. In addition to these stresses, however, AASHO also cited maximum loads of 16 to 23 metric tons (18 to 25 tons)/pile, which controlled pile design.

From 1940 to 1970, there was no organized effort on the part of timber pile producers or the wood industry in general to provide any guidance for setting allowable stresses for timber piles. The 1955 standard recommended that pile strength derivation follow principles presented in the Tentative Methods for Establishing Structural Grades of Lumber (ASTM D245-55) (6). The values were set by the pile users, represented by organizations such as AASHTO and AREA. National building code authorities and several state and city code authorities also published allowable timber pile capacities.

In 1970, ASTM adopted a consensus standard, Methods for Establishing Design Stresses for Round Timber Piles (ASTM D2899) (6). Methods presented in this standard determine the strength of full-sized piles on the basis of the strength of small clear samples of wood (ASTM D2555) (6) in a manner similar to that used to establish allowable lumber values. Standard D2555 lists mean strength (S) and standard deviation (σ) for tension, bending, and compression as well as modulus of elasticity and specific gravity of most commercial species available in the United States. These values pertain to small clear samples (5 by 5 cm (2 by 2 in.) cross section) taken from tree sections located 2.4 to 4.9 m (8 to 16 ft) above groundline. The samples are tested in the green condition at a strain rate to assure failure in less than 10 min.

Standard D2899, originally published in 1970, is intended to provide the link between clear wood stress values listed in ASTM D2555 to values for piles in ASTM D25. Standard D2899 provides derivations for compression parallel to the grain ($F_{c\parallel}$), bending (F_b), and horizontal shear (F_v), which are essentially estimates of fifth-percentile strengths at the pile tip adjusted for duration of load (λ). The pile tip strength is assumed to be normally distributed and the fifth percentile is estimated as 1.645 standard deviations below the mean.

Compression Parallel to Grain—The Standard D 2899 equation for compression parallel to the grain is

$$F_{c\parallel} = (S_{c\parallel} - 1.645\sigma_c)/1.88 \quad (1)$$

The adjustment (1/1.88) is the product of adjustments for the change in strength from butt to tip of a pile (0.9) and the grade and size effect of full-sized pile sections (0.9) on the basis of data presented by Wilkinson (19) and a duration of load factor (1/1.52). The duration of load factor was derived from the factor used in ASTM D245-69 to adjust $F_{c\parallel}$ for load duration and factor of safety (1.9), dividing by a 1.25 factor of safety.

Bending—For bending, the equation is

$$F_b = (S_b - 1.645\sigma_b)/2.04 \quad (2)$$

For bending, there is also an adjustment for change in strength from butt to tip (0.88) as well as an adjustment from small clear to full-size pile strength (0.9). Multiplying these factors by a load duration adjustment of 1/1.62 gives the adjustment factor of 1/2.04.

Horizontal Shear —The equation for horizontal shear is

$$F_v = (S_v - 1.645\sigma_v)/5.47 \quad (3)$$

The factor 1/5.47 is the product of a strength ratio of 0.75 and a factor of 1/4.1 taken from the ASTM D245-69 standard for softwood lumber shear stress to account for a combination of load duration, stress concentration and factor of safety.

Compression Perpendicular to Grain —The equation for compression perpendicular to the grain is

$$F_{c\perp} = (S_c)/1.5 \quad (4)$$

In this case, the denominator 1.5 is intended to account for average ring position and factor of safety.

These derivations include a formal factor of safety for shear and compression perpendicular to the grain but not for compression parallel to the grain or bending. The D2899 standard recommends safety factors of 1.25 and 1.3 for compression and bending, respectively, if “considered to be required” (6). The standard also points out, however, that the derivation is based on the weakest material (pile tip), which rarely sees full design load, and that end bearing piles are designed on the basis of minimum tip circumference; cross-sectional area and section modulus are larger than the minimum at every point along the length of the pile.

The D2899 standard also recommends that adjustments for preconditioning be applied to these values, depending on individual situations. The recommended adjustments for preconditioning are 1.0 for kiln drying, 0.9 for Boulton conditioning, and 0.85 for steaming.

Table 2 gives an example of pile allowable stress values published by the Uniform Standard Building Codes derived on the basis of the ASTM D2899 recommendations.

Table 2. Allowable stress values of timber piles

Species	Stress values ^{a,b} (MPa (lb/in ²))				Modulus of elasticity (MPa (lb/in ²))
	$F_{c\parallel}$	F_b	F_v	$F_{c\perp}$	
Douglas-fir ^c	8.6 (1,250)	16.9 (2,450)	0.79 (115)	1.58 (230)	10,300 (1,500,000)
Southetn Pine ^d	3.3 (1,200)	16.6 (2,400)	0.76 (110)	1.72 (250)	10,300 (1,500,000)
Red oak ^e	7.6 (1,100)	16.9 (2,450)	0.93 (135)	2.41 (350)	8,600 (1,250,000)
Red pine ^f	6.2 (900)	13.1 (1,900)	0.59 (85)	1.07 (155)	8,800 (1,280,000)

^a Stress values derived in accordance with ASTM 2899 standard, “Establishing design stresses for round timber piles”(6).

^b $F_{c\parallel}$ and F_b derived for pile clusters. When used individually, recommended safety factors are 1.25 for $F_{c\parallel}$ and 1.30 for bending.

^c Pacific Coast Douglas-fir.

^d Loblolly, slash, longleaf, and shortleaf pines.

^e Northern and southern red oak.

^f Red pine grown in the United States.

Several thorough reviews of the evolution of codes and standards that govern the design of timber piles have been published. Armstrong (9) reviewed the evolution of ASTM standards as well as knowledge on strength of timber piles that influenced the development of ASTM standard D2899. Armstrong also presented recommendations for adopting a Load Resistance Factor Design (LRFD) format for piles, along with adjustment factors that are slightly more conservative than those presented in D2899. Diekmann (12) discussed the evolution of timber pile allowable stresses as given by building codes and several design and performance standards. Davisson and others (11) published a general report on piles for the Federal Highway Administration, which provides an indepth discussion of timber pile allowable stress derivation and an LRFD format for comparing timber, steel, and concrete pile allowable values.

CONTROVERSY INVOLVING D2899 DERIVATIONS

The ASTM derivation of pile strength in compression and bending was empirically derived on the basis of test data presented by Peterson (15), Thompson (16), and Wilkinson (19). These test programs provided a valuable database for evaluating the sensitivity of pile strength to measurable physical properties. They indicate that the strength of wood varies along the length of a log and is significantly affected by member size, preconditioning temperature, and treatment. However, the data are insufficient for deriving a valid model to predict pile strength given physically measurable properties, such as the largest knot, total of knot diameters in a 1-ft section, specific gravity, and time and temperature of preconditioning. As a result of these limitations, the ASTM committee charged with writing D2899 based their adjustments on the average effects shown by the database and on accepted practice in wood design. The proposed adjustments to the ASTM D2555 clear wood stress values were assumed to be conservative on the basis of available data. However, the extent to which the values can be extrapolated beyond the range of the available data and still be considered valid is questionable.

Butt-to-Tip Strength

The butt-to-tip strength ratios (0.9 for $F_{c||}$ and 0.88 for F_b) were derived by comparing small clear tip strength to small clear butt strength for 15-m (50-ft) piles studied by Wilkinson (19). Data from both Wilkinson and Thompson (16) showed butt-to-tip reduction in specific gravity that correlated well with reduction in average strength. A 12 % to 15% reduction in standard deviation for Southern Pine specific gravity from the butt to the tip, as suggested by these data, led to the conclusion that the reduction factor for fifth-percentile strength is also 0.9 for $F_{c||}$ and 0.88 for F_b . Despite the fact that Wilkinson's data showed that specific gravity increased from butt to tip for red oak, a general assumption was made that these factors applied regardless of species or pile length.

The effect of size and imperfections was also an empirical derivation. Results reported by Thompson (16) and Wilkinson (19) show that variation in the sum of measured knots in a 1-ft section or the largest single knot describes less than 5% of the variation in pile strength. Although these authors felt that imperfections have a detrimental effect, any relationship derived on the basis of such poorly correlated data has little significant meaning. Therefore, the effects of imperfections and size were combined and evaluated as a ratio of full-size tip strength to small clear tip strength. The average reduction in both bending and compression parallel to the grain was 0.9.

Preservative Treatment Effects

Effects of preservative treatment on the strength of wood have been of concern for over 80 years. Past studies (10,14,15,16,20) on creosote-treated wood suggest that strength reductions are primarily due to conditioning prior to treatment. However, Eaton (13) showed definite differences in residual strength of piles treated with creosote, chromated copper arsenate (CCA), and ammoniacal copper arsenate (ACA). Because many different factors were involved in past studies, there is no clear agreement on the effects of preconditioning

and treatment on strength of timber piles. Available data suggest that the ASTM recommendation for conditioning adjustments are slightly unconservative.

Available data on the effects of kiln drying on strength of full-size round timbers are very limited. Wilkinson (19) compared strength of Southern Pine pile sections kiln dried to 30% to 40% moisture content and re-soaked to the green condition. The kiln-dried specimens, subjected to temperatures ranging from 57°C (134°F) to 74°C (165°F) for 164 h averaged 12% weaker in compression parallel to the grain than the green specimens, with little change in variability. However, specimens that were both kiln dried and treated showed strength equal to or greater than green specimens. Wilkinson hypothesized that the apparent increase in strength of kiln-dried and treated sections was due not to creosote itself, but to the fact that the petroleum carrier for the treatment prevented moisture from reentering the cell wall upon re-soaking. These data alone do not support the conclusion that treatment counteracts the negative effects of kiln drying temperatures. Thus, this study does not support the ASTM D2899 recommendation of no reduction for kiln drying.

The Boulton process for conditioning piles prior to treatment is more commonly used than kiln drying. Three studies that include data on round timbers conditioned using this process are discussed in reports by Eaton and others (13), Peterson (15), and Wood and others (20). The report by Wood and others includes data on bending tests of Douglas-fir and larch poles. The results show strength reductions on full sections ranging from 7% to 18%. For small clear tests, strength reductions ranged from 3% to 14%. The studies by Peterson and Eaton compare the strength of treated and untreated Douglas-fir pile sections; however, neither study provides any information about the treatment process other than to say that retentions met AWWA standards. The Boulton process is assumed because it is the common practice in treating Douglas-fir. Peterson's data show little change in the average value of compressive strength, but the strength coefficient of variation increased from 28% for untreated specimens to 34% for treated specimens. Eaton evaluated small samples of Douglas-fir pile sections in compression and bending strength under several treatment conditions. For 5 creosote-treated piles, the results were an 18% reduction in bending, for 10 piles treated with ACA and creosote 27% reduction in bending and 19% in compression, for 10 piles treated with CCA and creosote 54% reduction in bending and 30% in compression, and for 5 piles treated with ACA alone 33% reduction in bending and 27% in compression. While Peterson's results make the ASTM recommendation appear conservative, results from Eaton and Wood strongly suggest that strength reductions are probably greater than 10%.

Steam conditioning conducted by the AWWA C3 standard for piles is perhaps the most controversial issue in the ASTM D2899 standard. The ASTM pole research program conducted in the late 1950s indicated that steam conditioning strength reductions ranged from 30% for poles to 17% for small clear tests. The poles were steam conditioned for 15 h at 121°C (250°F). Thompson's (17) tests of 50 matched pairs of Southern Pine pile sections showed a 23% reduction for full-sized pile sections and 20% for small clears of Southern Pine steam conditioned for 15 h at 118°C (245°F). Eaton's (13) bending tests of Southern Pine pile sections showed strength reductions ranging from 26% for sections treated with creosote to 48% for piles treated with both CCA and creosote. No information was given in Eaton's study about time and temperature of the conditioning process, but the treaters presumably followed the recommendations of the AWWA C3 standard.

Load Duration and Factor of Safety Adjustment

ASTM D2899 adjustments for factors other than member size, imperfections, and location of section along the length of the pile were borrowed from the 1970 revision of ASTM D245 (6) standard for deriving design stresses for dimension lumber. In the case of $F_{c\parallel}$ and F_b , adjustments of 1.52 and 1.62 are intended to account for duration of load. For F_v , the adjustment is intended to account for stress concentrations caused by defects, load duration, and factor of safety. For $F_{c\perp}$, the adjustment is intended to account for annual ring orientation and factor of safety.

These adjustments are inconsistent and some of them have little meaning for timber piles. There is no basis for assigning a different load duration factor for compression and bending. A stress concentration factor derived for lumber has little meaning when applied to poles, where fiber continuity around knots will result in

less stress concentration compared to lumber, where fibers around the knot have been cut off at the surface of the board. Finally, the annual ring orientation for $F_{c\perp}$ is always the same for a round timber, and ASTM D245 has changed the adjustment from 1.5 to 1.67.

DESIGN FORMAT FOR LOAD RESISTANCE FACTOR

In addition to the need for minor revisions or improved supporting data for allowable stress derivations, the ASTM D2899 standard would be enhanced by converting from the current working stress design to a LRFD format. The wood industry has generally supported efforts to adopt an LRFD format, which would make wood design procedures more compatible with those used for competing materials and facilitate implementation of future design improvements. An initial conversion to the LRFD for piles would simply be a conversion in format, with no new data required. However, guidelines being developed for a reliability-based LRFD should provide an economic incentive for improving the knowledge base to more accurately define the strength of timber piles.

Current design procedures follow a “working stress” design format, which targets estimates of fifth-percentile strengths ($R_{0.05}$) to satisfy the equation

$$\lambda R_{0.05}/\gamma \geq D + L \quad (5)$$

where

λ is load duration,
 γ factor of safety,
 D dead load, and
 L live load.

The LRFD approach takes the form

$$\lambda \phi R_n \geq 1.2D + 1.6L \quad (6)$$

where ϕ is resistance factor, dependent upon failure mode, and R_n nominal resistance. If we assume that for piles the ratio $D/L = 1$, then

$$\lambda R_{0.05}/(2\gamma) = \lambda \phi R_n/2.8 \quad (7)$$

and

$$R_n = 1.4(R_{0.05})/(\phi\gamma) \quad (8)$$

If ϕ is assumed to be 0.8 and γ is taken as 1.25, then

$$R_n = 1.4R_{0.05} \quad (9)$$

which gives an initial estimate of a nominal resistance to be used for pile bearing stress. Future improvements, such as an improved database for timber piles or improved models for evaluating in-place loads and stresses on timber piles, should provide more accurate estimates of the nominal resistance as well as the load side of Equation (6).

CONCLUSIONS

Because of the difficulty of accurately predicting the interactive load capacity of soil and pile, foundation engineers tend to err on the conservative side when assessing the capacity of a pile group. Consequently, few notable timber pile overload failures have occurred. As more accurate models are developed, however, the importance of an accurate assessment of pile strength will increase. Those wishing to use timber piles should be aware of the derivation of design values given in ASTM D2899. The available pile strength database shows significant differences between the strength of small clear wood and that of a full-size pile tip, but insufficient data are available to separate individual contributing factors such as knot size, location of section along pile length, or size of pile. The adjustments currently recommended in ASTM D2899 for these factors are warranted. It is the author's opinion, however, that duration of load adjustments should be 1.62 for all stresses, factor of safety should either be included or excluded from all derivations, and ring orientation factor should be removed from the $F_{c\perp}$ equation. Finally, more conservative adjustments (0.9 for kiln drying, 0.85 for Boulton conditioning, and 0.75 for steaming) should be used for conditioning effects until better data or analytical models are provided.

Pressures to replace working stress design with a load resistance factor design format should provide an incentive for the more progressive members of the timber pile industry to develop stronger support for the derivation of pile load capacities. Currently, LRFD formats are being used for steel and concrete pile foundations. To maintain its share of the market, the timber pile industry must develop procedures for determining nominal timber pile load capacity in a manner that will ensure a level of safety comparable to that provided for steel and concrete. This will require an understanding of the current derivation of timber pile allowable stresses and the extent to which the deviation is supported by test data.

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