The use of untreated timber piles as foundation support in Europe and the U.S became more wide-spread at the end of the 19th century and beginning of the 20th century, when industrialization led to the rapid expansion of urban areas. Their use was common in regions with natural soft soils, or where urban-fill was used for land development, such as in the northeastern U.S. Thousands of historic structures across Europe and the U.S. currently remain supported on untreated timber piles; their continued use and maintenance costs highly depend on the condition of the piles after tens or hundreds of years of in-ground service.

Early on, it was recognized that untreated timber piles needed to be submerged to provide anoxic (i.e. little to no oxygen) conditions, which was thought to prevent pile deterioration due to wood-destroying fungi and/or soft rot attack. Therefore, the installation of untreated timber piles typically required the pile cutoff to be below the lowest expected in-service groundwater level. Unfortunately, urban development resulting from the industrial revolution brought with it underground construction; and as a consequence, groundwater levels became lowered due to long-term construction dewatering, new underground structures acting as obstructions to groundwater flow, and leaks into poorly sealed basements and underground utilities. The lowered groundwater levels resulted in exposure of the timber pile tops to oxygen, leading to significant pile-top deterioration due to fungal attack, and ultimately, significant settlement of the structures.

The typical foundation repair method for deteriorated untreated timber piles is cut-and-post underpinning; an access pit is excavated along the length of the foundation and the tops of the timber piles are exposed, removed, and replaced with new structural elements, e.g. concrete posts or concrete-encased steel posts.

It took until the 1970s to identify that biodeterioration of timber piles can also be caused by bacteria (Boutelje et. al. 1968, Klaassen 2008-1). And it was not until recently that more comprehensive studies performed in Europe, specifically the BAC-POLES scientific project funded by the European Commission in 2001 (Klaassen 2005), have been able to quantify the rate of bacterial attack and of related degradation of the submerged wood strength.

This article, Part 1 of a 2-Part series, provides a summary of the state of knowledge on bacterial biodeterioration on submerged and untreated timber piles, as well as a discussion on the impacts of time and deterioration on the in-service compressive strength of the piles. A method for performing qualitative assessment of the likely effectiveness and durability of cut-and-post underpinning remediation of untreated timber-pile supported structures will be proposed in Part 2.

Biodegradation of Untreated Submerged Timber Piles

Until recently, bacterial attack on submerged wood was the least understood biodeterioration mechanism. The European BAC-POLES research project, which investigated causes and patterns of bacterial decay in timber piles in the early 2000s, as well as subsequent research performed primarily in the Netherlands, have shed much needed light on the nature of bacterial deterioration mechanisms. It is now thought that bacterial decay of timber piles occurs always, at all sites and in all conditions, although the rate and degree of attack may vary depending on site specific conditions The following list is a summary of the most salient results and conclusions in the literature, relative to bacterial attack of submerged timber piles, reached to date:

- Bacterial wood degradation can occur under a wide range of conditions due to the variety of bacteria species, each with its own optimal environmental settings (Klaassen 2008-1, Nilson et. al. 2008).
- In addition to low levels of oxygen, wood-degrading bacteria also appear to thrive best in environments with low levels of nitrogen (Huisman et. al. 2008).
- Bacterial wood degradation occurs uniformly along the entire pile length (pile lengths of up to about 46 feet were included in the BAC-POLES study). Thus, in terms of assessment of bacterial degradation, the condition of the pile tops is representative of the entire pile (Klaassen 2008-1).
- Slight cell wall deterioration due to bacterial attack results in no major loss of compressive strength (Klaassen 2008-1). On the other hand, severe cell wall deterioration due to bacterial attack results in softening of the wood, significantly reducing the compressive strength of the wood in the affected areas and, thus, the effective available load-bearing pile cross-section.
- The velocity of bacterial decay is variable between wood species and is generally slow, ranging between almost 0 to more than 1 mm/year (0.04 inch/year). Based on a database that included about 1000 spruce piles and 1000 pine piles with a service life ranging between 80 to 200 years, the rate of initial advancement of bacterial invasion before significant wood strength loss occurs is about 0.5 mm/year (0.02 inch/year) in pine, whereas in spruce it ranges between 0.1 to 0.5 mm/year (0.004 to 0.02 inch/

*Giuliana Zelada-Tumialan, P.E., is Senior Project Manager at Simpson, Gumpertz & Heger, Inc., Giuliana may be reached **atgazelada@sgh.com**.*

*William Konicki, P.E., is Senior Principal at Simpson, Gumpertz & Heger, Inc. William may be reached at **wpkonicki@sgh.com**.*

*Philip Westover, P.E., is a Staff Consultant at Simpson, Gumpertz & Heger, Inc. Philip may be reached at **plwestover@sgh.com**.*

*Milan Vatovec, Ph.D., P.E., is Senior Principal at Simpson, Gumpertz & Heger, Inc. Milan may be reached at **mvatovec@sgh.com**.*

year). Once bacterial invasion is well established, the rate of deterioration increases; the average rate of severe bacterial attack causing significant wood strength loss was calculated to be about 0.25 mm/year (0.01 inch/year) in pine piles, and about 0.13 mm/year (0.005 inch/year) in spruce piles (Klaassen 2009).

- The advancement of bacterial decay occurs inwards, starting from the pile perimeter. For spruce and pine piles with an in-service age of 650 years or less, the rate of bacterial attack decreases significantly at the heartwood-sapwood interface. Bacterial degradation of the heartwood was only observed in oak piles about 2000 years old; the degree of deterioration in the heartwood varied from moderate at the heartwood-sapwood interface to weak near the pith (Klaassen 2009).

- Wood species with more permeable tissue structures (e.g. alder, poplar, and the sapwood of pine and oak) are more susceptible to bacterial decay than those with less permeable tissue structures (e.g. spruce and the heartwood of pine and oak). More permeable tissue structures, i.e. wood species with larger open cross-field pits, allow more flow of water and therefore transport of wood-degrading bacteria in the water stream across the pile cross-section (*Figure 1*). In the presence of pressure gradients between the tops and bottoms of piles (i.e. the bottom and top of the piles are embedded in different soil layers with different groundwater levels), water flow and transport of wood-degrading bacteria is facilitated along the length of the piles (Klaassen 2008-2).

The authors' observations, and observations by others, regarding a large number of piles exposed over most of their length confirm that bacterial decay occurs over the entire pile length. In addition, microscopic evaluations on spruce timber pile samples from one of the authors' projects in the northeastern U.S. (for which historic records on timber-pile condition assessments are available), indicate the following:

- Slight to no cell wall deterioration combined with the presence of bacteria was observed at depths ranging from 0.25 to 4 inches (6 to 100 mm) for piles with 67 to 117 years in service. The calculated average rate of advance of bacterial invasion is 0.41 mm/year (0.016 inch/year).

Figure 1: Deteriorated timber pile cross-section.

- Severe cell wall deterioration with significant strength loss was observed in the outer 0.5 to 0.75 inches (13 to 19 mm) for piles with 103 years to 117 years in service. The calculated average rate of advance of severe degradation is 0.13 mm/year (0.005 inch/year).

Therefore, the behavior of microbial decay under submerged conditions in the U.S. appears to be similar to that observed by others in European piles of the same species and of equal or greater age.

Compressive Strength of In-Service Timber Piles

Current design standards for new timber pile foundations (ASTM D245-06 and ASTM D2899-03) reference and use the allowable compressive strength of timber piles, rather than the ultimate compressive strength (strength at failure). The design strengths are based on, but are lower than, the representative ultimate compressive strength obtained from testing of clear, straight-grained, green wood samples. The ultimate compressive strength value is multiplied by a series of adjustment coefficients that are meant to account for a safety factor, duration of load (DOL) effects, grade/quality of wood, pile group effects, test sample size, variability, and potential defects in the wood. Of all these factors, the most significant in terms of reduction in compressive strength is the DOL factor, which imposes approximately a 40% reduction in the compressive strength for permanent (constant) loads (ASTM D245-06). The DOL factor accounts for the laboratory-testing proven effects of duration of the applied load on the strength properties – the longer the wood is subjected to a constant load, the lower its strength. This is due to unrecoverable microdamage that takes place during the period the pile is loaded. Although the use of all these

adjustment factors for design purposes is prudent and necessary, their use for evaluation of existing conditions is likely conservative.

Other than reductions in strength due to the DOL factor, current design standards assume no reduction in the compressive strength of wood due to aging effects, (provided no biodeterioration is present). This is reportedly based on strength tests of old timbers, 100 or more years old, which showed no appreciable deterioration of the wood's strength or stiffness due to age alone (ASTM D245-06). Klaassen (2008-1) reached a similar conclusion when comparing the compressive strength of foundation piles that had been in use for more than 80 years (and suffered no bacterial or other degradation) with compressive strength of samples obtained from freshly sawn timbers.

Van Kuilen (2007), however, concluded that the compressive strength of submerged timber decreases with time. He presented results of compressive strength tests performed on clear wood samples obtained from submerged untreated European pine, spruce, larch, oak and alder piles with varying in-ground service ages (between 70 and 640 years). The results are presented as the ratio of the measured compressive strength (parallel to the grain) of the aged wood to the average strength of new wood in a wet condition, versus the time in service in the ground below the groundwater level (*Figure 2*). Van Kuilen further determined that the residual strength of the timber piles appears to be governed by the amount of heartwood in the cross-section (based on the results of tests on full pile cross-sections), and provided bestfit lines for estimating the decrease in timber pile compressive strength of the heartwood and sapwood as a function of time in service and under load. Van Kuilen did not elaborate on the cause of strength reduction with time beyond indicating that the magnitude of applied load (i.e. accumulation of mechanical damage under sustained loading) and the degree of decay likely play a role.

To validate the use of Van Kuilen's curve for estimating the decrease in compressive strength of heartwood, the author's calculated strength ratios (i.e. ratio of measured compressive strength of aged pile to the expected compressive strength of a new pile) for full timber pile cross-sections and clear wood samples obtained from piles exposed at various projects throughout northern U.S. All full-timber pile samples considered were eastern spruce; clear wood samples considered were eastern spruce, red pine, and elm. The in-service age of the samples ranged from 67 to 137 years. Only non-deteriorated heartwood samples were included in this evaluation.
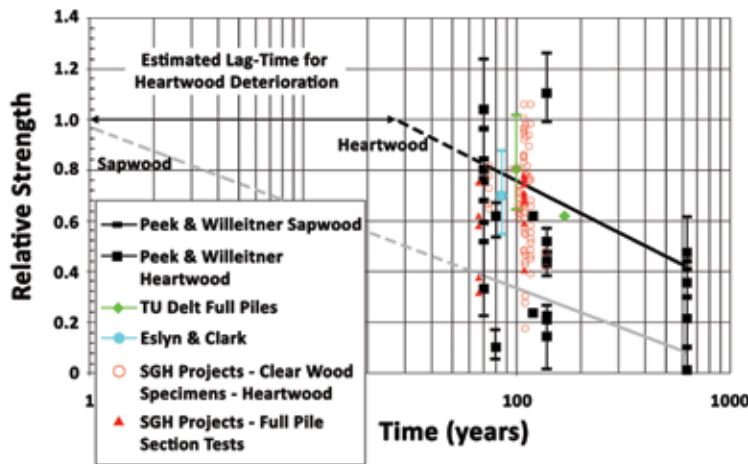
Figure 2: Decrease in timber pile compressive strength with in-service age (Base figure from Van Kuilen, 2007).

For comparison with Van Kuilen's curve, the expected average clear wood ultimate compressive strengths parallel-to-the-grain of 2650, 3280, and 3780 psi (18.2, 22.6, and 26 MPa) were used for spruce, pine, and elm piles respectively. These values were obtained from published average strength values for each wood species grown in the U.S. and Canada, as provided in Tables 2 and 3 of ASTM D-2555-06. *Figure 2* shows a plot of the calculated strength ratios superimposed on Van Kuilen's graph. In general, the data is reasonably centered and distributed around the best-fit line for decrease in compressive strength of submerged untreated pile heartwood proposed by Van Kuilen.

The laboratory compressive strength testing of samples obtained from existing timber piles includes the effects of any micro-damage, i.e. duration of load effects, that has taken place during the period the pile has been in service. Conversely, the laboratory compressive strength testing of samples from freshly-sawn timbers do not, and the published ultimate strength values are applicable for short-term loading only. Therefore, it appears that Van Kuilen's curves reflect the decrease in compressive strength of submerged, undeteriorated heartwood due to aging under prolonged continuous loading (i.e. DOL).

The spread in the values of compressive strength parallel-to-the-grain obtained at various service ages could be related to variations in the level of applied compressive stress on the piles. Microscopic mechanical damage to timber piles under sustained loading, however, becomes less significant if the piles are loaded to a smaller fraction of their capacity. Hoyle and Woeste (1989) report that when the applied stress is at less than 55%

of the short-term ultimate wood strength, creep deflection levels off and additional deflection does not occur. As the applied stress levels increase to more than 55% of the short-term ultimate wood strength, creep continues indefinitely and ultimately results in failure. Thus, a pile loaded to 10% of its ultimate short term test capacity is likely to experience less damage under sustained loading than a pile loaded to 50% of its ultimate short term test capacity. For example, in large historic structures, where the number of in-place timber piles sometimes exceeds the minimum number of piles required to support the applied loads by design, the piles can be expected to have experienced a low level of sustained applied loads and hence less "aging/DOL" effects.

Interim Remarks

The authors' experiences confirm that bacterial attack in the submerged portion of the timber piles can play an important role in limiting the estimated remaining service life of pile-supported structures, even after cut-and-post underpinning has been performed. Given the magnitude of involved costs, the presence and impact of bacterial attack may ultimately govern the choice of the underpinning method to be used. The current understanding of the rates of deterioration, loss of strength and loss of stiffness of wood with time is still developing. However, there is sufficient information available to allow for a qualitative assessment of the likely effectiveness and durability of cut-and-post underpinning remediation of untreated timber-pile supported structures.▪

References

Boutelje, J.B., and Bravery, A.F. (1968), "Observations on the Bacterial Attack of Piles Supporting a Stockolm Building", *J. Inst. Wood Science*, 4(2):47-57.

Huisman, D.J., Kretschmar, E.I., and Lamersdorf, N. (2008), "Characterising Physicochemical Sediment Conditions in Selected Bacterial Decay Wooden Pile Foundation Sites in the Netherlands, Germany and Italy", *International Biodeterioration and Biodegradation* Vol. 61:117-125.

Klaassen, R.K.W.M (2008-1), "Bacterial decay in wooden foundation piles – Patterns and causes: A study of historical pile foundations in the Netherlands", *International Biodeterioration and Biodegradation* Vol. 61:45-60.

Klaassen R.K.W.M. (2008-2), "Water Flow Through Wooden Foundation Piles: A Preliminary Study", *International Biodeterioration and Biodegradation* Vol. 61:61-68.

Klaassen R.K.W.M. (2009), "Factors that influence the speed of bacterial wood degradation", International Conference on Wooden Cultural Heritage, Hamburg, October 2009.

Hoyle and Woeste (1989), *Wood Technology in the Design of Structures, 5th Edition*, Iowa State University Press.

Meyerhof, G.G. (1976), "Bearing Capacity and Settlement of Pile Foundations", *J. of the Geotechnical Engineering Division*, GT3, March 1976.

Nilson, T. and Bjordal, C. (2008), "Culturing Wood-Degrading Erosion Bacteria", *International Biodeterioration and Biodegradation* Vol. 61:3-10.

ASTM D245 – 06, Standard Practice for Establishing Structural Grades and Related Allowable Properties for Visually Graded Lumber.

ASTM D2555 – 06, Standard Practice for Establishing Clear Wood Strength Values.

ASTM D2899 – 03, Standard Practice for Establishing Allowable Stresses for Round Timber Piles.

National Design Specification (NDS) for Wood Construction with Commentary and Supplement: Design Values for Wood Construction 2005 Edition, ANSI/AF&PA NDS -2005, American Forest & Paper Association, Inc.

Vatovec, M., and P.L. Kelley, "Biodegradation of Untreated Wood Foundation Piles in Existing Buildings – Remedial Options," *STRUCTURE magazine*, Dec. 2007.

Vatovec, M., and P.L. Kelley, "Biodegradation of Untreated Wood Foundation Piles in Existing Buildings – Deterioration Mechanisms," *STRUTURE magazine*, Sept. 2007.

Vatovec, M., and P.L. Kelley, "Biodegradation of Untreated Wood Foundation Piles in Existing Buildings –Investigation", *STRUCTURE magazine*, June 2007.