Acetylated Wood in Structural Applications

Ferry Bongers[1], John Alexander[2], André Jorissen[3], Hans J. Blaß[4], Callum Hill[5]

[1]Titan Wood BV, P.O. Box 2147, 6802 CC Arnhem, the Netherlands [email: ferry.bongers@titanwood.com]

[2]Titan Wood Limited, 66 Hammersmith Road, London W14 8UD, UK [email: john.alexander@titanwood.com]

[3]Eindhoven University of Technology, P.O. Box 513, 5600 MB Eindhoven, the Netherlands [email: a.j.m.jorissen@tue.nl]

[4]Karlsruhe Institute of Technology, Reinhard-Baumeister-Platz 1, D-76131 Karlsruhe, Germany [email: Blass@kit.edu]

[5]Napier University, Edinburgh EH10 5DT, UK [email: C.Hill@napier.ac.uk]

Keywords: Acetylation, Eurocode 5, mechanical properties, wood modification, timber engineering

ABSTRACT

Since the commercial introduction of acetylated wood on the market by Titan Wood in 2007, Accoya® wood has been applied in many different ways. In general, wood modification opens a whole new and broad range of innovative or renewed applications for timber. Timber may now also be used in structures previously made in steel, synthetic materials or concrete. An example is the heavy load-bearing traffic bridge constructed using Accoya® wood at Sneek in the Netherlands for which the whole process of design, fabrication, and project monitoring were commissioned by the principal to enable the bridge design and construction. All results are specific to this bridge and a second bridge of the same form is now in construction. Standardised testing is required to describe the performance of Accoya® in the wide range of structural application. This paper presents an overview of the properties of acetylated wood and discusses how this might be considered in the current regulations for structural applications.

INTRODUCTION

Use of wood in structural applications

Due to its properties (*e.g.* strength to weight ratio), its ease to process and its availability, wood has been used for structural applications throughout history. Wood is also a renewable material, which is, when used properly, completely in balance with the natural surroundings. However, since it is a product of nature, wood has a time limited life. At the end of its service life it goes back into its basic constituents of carbon dioxide and water through biological, thermal, aqueous, photochemical, chemical, and mechanical degradation processes. Most time limiting (durability) problems are associated with wood destroying fungi under high humidity conditions. Associated maintenance and decay risk raise, perceived or real represent the major barrier to increased use of timber in *e.g.* bridge design. Furthermore, due to water changes, moisture absorption and desorption, resulting in swelling and shrinkage, stresses develop, resulting in surface cracking (desorption) or internal cracking (adsorption). Additionally, wood exposed to outdoor climate undergoes photochemical degradation caused by ultraviolet radiation.

The service life of untreated wood depends on the natural durability of the wood species. Many tropical hardwoods are known for their durability characteristics. However, a vast majority of the world's wood species do not possess inherent durability, dimensional stability and other valued characteristics. The world's supply of durable wood species suitable for long term performance in outdoor applications is becoming scarcer and there are detailed reports of second growth natural durable timbers failing prematurely (Araki *et al.* 2010). Furthermore, environmental regulations on the use of biocides (preservatives) to enhance the durability of wood are increasing. With special focus on the so called durable design, *e.g.* use appropriate covering for horizontal parts, part of the problems associated with natural durability of wood can be overcome. Further, by appropriate maintenance, wood can be fulfilling its purpose for a long time. However, nature is programmed to recycle and can have rapid effect when protective design systems fail.

Acetylated wood

An 'environmentally friendly' alternative is the chemical modification of wood which results in improved wood performance. By altering the wood matrix on a molecular level, the properties of wood species with low durability can be enhanced. Acetylation with uncatalyzed acetic anhydride is well known to increase the resistance of wood against wood decaying fungi as well as improving the dimensional stability under varying moisture conditions. The reaction of acetic anhydride with wood results in esterification of the accessible hydroxyl groups in the cell wall to acetyl groups with the formation of by-product acetic acid (see Figure 1).

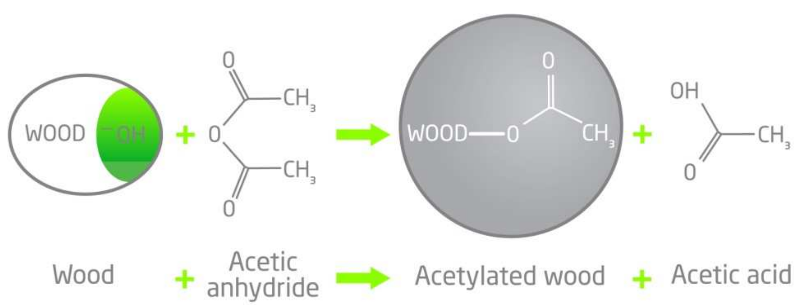

Figure 1: Schematic reaction of acetic anhydride with wood

A comprehensive background of acetylation and wood modification in general is given by Hill (2006), Homan and Jorissen (2004), Jones (2007) and Rowell (2006).

Titan Wood (www.titanwood.com) has introduced acetylated wood named Accoya® wood (www.accoya.com) on the market in 2007. Accoya® wood is based on the acetylation of radiata pine (*Pinus radiata* D. Don) and is mainly used for applications such as joinery, cladding, decking and (light) civil works in the Netherlands, UK and Germany (Alexander 2007, Bongers *et al.* 2009, Kattenbroek 2005).

Nowadays, the countries and market segments in which Accoya® wood is used is expanding. Furthermore, by acetylation of other wood species, new market segments can be addressed. Besides applications in which currently wood is used, acetylated wood, and in general modified wood treated differently, can open a whole new and broad range of innovative or renewed applications for timber where previously steel, synthetic materials or concrete was used. An example is the heavy load-bearing traffic bridge constructed using Accoya® wood at Sneek in the Netherlands (Tjeerdsma *et al.* 2007, Tjeerdsma and Bongers 2009, Jorissen and Lüning 2010).

USE OF ACETYLATED WOOD IN STRUCTURAL APPLICATIONS

The whole process of design, fabrication, and project monitoring of the heavy load-bearing traffic bridges in Sneek were guided by research institutes, working on behalf of the principal. Although many tests were performed, more standardised testing is required to fully describe Accoya® wood structural properties and enable its use in a wide range of applications. An overview of the current regulations and standards for structural applications and changed properties due to acetylation is presented below. The current certification schemes for modified wood are also described. Finally the service life and environmental impact of acetylated wood is discussed.

Regulations and standards

Wood used in structural applications needs to address the building codes and other regulations in the specific country. As part of harmonisation work in Europe within the Construction Products Directive (CPD) the required information of a building product is described for CE marking. The European Norm EN 1995, or "Eurocode 5: Design of timber structures" is a standardised European design code that establishes common rules across the European Union for structural design of timber buildings. The target of a designer is to ensure an adequately durable structure that fulfils the requirements of the building code and the principal / user. In order to do so many factors needs to be evaluated; for instance required performance criteria, expected environmental conditions, maintenance intervals and the composition, properties and performance of the used materials.

For wooden elements the resistance to biological organisms shall either have adequate natural durability for the particular hazard class or be given a preservative treatment. Furthermore, for structural application, “timber shall be strength graded in accordance with the rules ensuring that the properties of the timber are satisfactory for use and especially that the strength and stiffness properties are reliable”. Either visual grading or machine graded timber according to EN 14081 series fulfils this criteria. The characteristic strength and stiffness values and densities should be determined according to EN 408 and graded according to EN 384. For glued laminated timber additional performance requirements are described in EN 386, finger joints shall comply with EN 387 and graded according to EN 1194. Finger jointed structural timber shall comply with EN 385.

Changed properties by acetylation

The polymeric structure of wood mainly consists of cellulose, hemicellulose and lignin. These components contribute in different ways and degrees to the mechanical properties of wood (Winandy and Rowell 1984). Any chemical or thermal modification method that affects the chemistry of the wood cell wall polymers and/or their interactions must therefore affect the physical and mechanical properties of the wood (Rowell 1996). The affect will be different regarding different wood modification processes. A detailed study of the affect of thermal treatment on mechanical properties was made by Boonstra *et al.* (2007).

Due to acetylation, chemical changes of the wood cell wall polymers are evident; the moisture absorption behaviour of the cell wall is altered due to reactions of acetic anhydride with the hydroxyl groups. This results in a reduced Equilibrium Moisture Content. Furthermore, the density of the wood increases due the weight of the added acetyl groups. However, also the wood swells during acetylation resulting in fewer fibres per cross section than with the unmodified wood. The mechanical properties of acetylated wood have also been studied extensively, mostly on clear samples (Bongers and Beckers 2003, Dreher et al 1964, Epmeier *et al.* 2007a, 2007b, Jorissen *et al.* 2005, Larsson and Simonson 1994, Norimoto *et al.* 1992, Rowell 1996, Rowell *et al.* 2009). Many researches concentrate on bending stiffness and strength. Tests to determine tensile strength, compression strength, shear strength, hardness, impact bending strength, creep and toughness have also been performed. However, based on the existing literature it is difficult to make hard conclusions on the exact number of the effects of acetylation on these mechanical properties due to variation in test results. This is most likely caused by the fact that the chemistry of the cell wall polymers and other characteristics vary (slightly) per wood species, within a wood species and even within a board. Furthermore, the type of applied acetylation process varies and even the affect on the properties can be different from one batch to another (Bongers and Beckers 2003). The variation of test results in larger elements, instead of small defect free sample, is increasing due to occurrence of defects in wood, such as knots, reaction wood, resin pockets, abnormal slope of grain and checks decrease the structural properties (Boonstra *et al.* 2007, Jorissen *et al.* 2005).

Besides mechanical properties, other properties, which are important for structural applications, are also changed by the acetylation process. Most obvious is the enhanced durability and dimensional stability of acetylated wood and its reduced response to climatic changes in relative humidity. However, other properties such as corrosion sensitivity of metals can also change. For glued laminated structures, bonding is important. Due to the physical and chemical changes of the wood due to acetylation not all commercially available adhesives are suitable and gluing processes need to be studied more in detail (Vick and Rowell 1990).

Design life expectation and environmental impact of acetylated wood

For any structural design, it is of importance to ensure an adequate design life. Although all materials are vulnerable for degradation, timber is considered to decay more quickly than steel or concrete in wet exterior applications. Inherently durable (or preserved) timbers can be used either partially or fully exposed to the weather. However, the only way to guarantee a life in excess of 35 to 40 years is to completely protect the structure from wetting (Lawrence 2008). A design life of 50 years for Ekki, 90 years for reinforced concrete and 50 years of (hot dip galvanized) steel was used in an environmental impact study of a typical pedestrian bridge (Van der Lugt *et al.* 2010). For Accoya® wood a design life of 80 years was used. Sustainable source Ekki has the lowest environmental impact, followed by Accoya®, concrete and steel. Unsustainable source Ekki has a high rating to account for the wastage of timber at forest sites where logs are harvested in this manner. Sustainably sourced timber bridges offer clear environmental benefit compared to non wood materials. Additionally Accoya® provides a long service life.

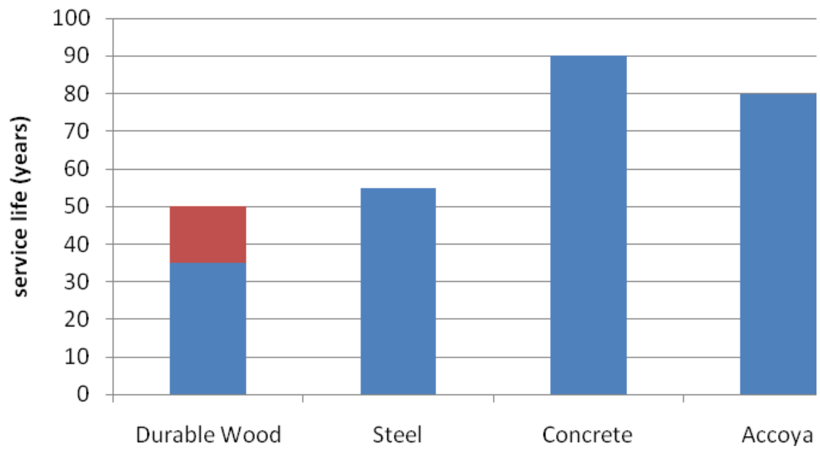

Figure 2: Design life of different building materials for timber bridges (sources Lawrence 2008 for durable wood and Van der Lugt 2010 for durable wood and others. Red section for durable wood expresses the differences in the two sources)

Certification and production control of modified wood

For market introduction, the building product has to at least comply with the building codes and regulations for the applicable market. In addition to these minimum requirements, certification may be demanded or strongly desired by the market. Certification can be divided into three categories: certification of the acetylation process, certification of the acetylated wood and certification of the final product. In the Netherlands, a National Assessment Directive was established to certify modification processes under the private label KOMO® (BRL 0605, Homan and Tjeerdsma 2005). Part of this certification is focussed on control of production consistency and repeatability of the process. The other part is related to the properties of the modified wood and is mostly concentrating on joinery applications. Based on these properties the modified wood can then be evaluated for its suitability in joinery in the Netherlands (SKH-Publicatie 97-04) and in Germany (VFF Merkblatt HO.06-4). In most countries, however, no schemes are available for evaluating modified wood.

Appropriate assessment for modified wood

For structural applications no specific evaluation schemes are available for modified wood. Widmann (2009) demonstrated the difficulties of introducing thermally modified beech (*Fagus sylvatica*) into the European strength class system EN 338. He concludes that the thermally modified beech should be regarded as a completely new material, rather than just a slight modification of a known wood species. Furthermore Widmann discusses the impact of the changed properties on various modification factors used in the Eurocode 5.

Regarding EN 1194 a serious problem arises. EN 1194 requires the basic properties bending strength, mean modulus of elasticity and density for determining other strength and stiffness properties. However, for evaluating the relationships given in EN 1194 untreated European (coniferous) wood species are used. It is not known whether these relationships hold for other species, like acetylated wood, as well.

Another discussion item forms the question if the testing methods currently used are still appropriate to test the behaviour of modified wood. When should machine strength grading be performed, after or prior to the acetylation? Most probably, the relationships used during machine test grading (machine settings) do not hold for modified wood and the settings must be developed completely.

CONCLUSION AND OUTLOOK

Despite the extensive scientific research noted on physical and mechanical properties of acetylated wood, more testing and model development is required to take the product forward through to an accepted structural approval. The impact of acetylation in literature varies by wood species, type of processes and between batch variations. Furthermore, the suitability of the current standards to evaluate the strength and stiffness properties of modified wood species as well as the design calculations may not be appropriate. Any approach taken will require support from appropriate production control including strength grading to ensure all building elements have the required properties.

In general many discussions exist regarding how to evaluate acetylated wood and in general modified wood for use in heavy structural applications. To harmonise effects in this area, involvement of the scientific community and legislation is critical. An option in Europe is the construction of an European Technical Approval (ETA), a harmonised standard or use of country specific approvals.

REFERENCES

Araki, S., Hirasawa, H., Sasaki, T., Nakamura, N. And S. Usuki (2010). A study on predicting the lifetime of timber bridges. In: *Proceedings of 11th World Conference on Timber Engineering*. Riva del Garda, Trentino, Italy.

Alexander, J. (2007). Accoya™. An Opportunity for Improving Perceptions of Timber Joinery. In: *Proceedings of the Third European Conference on Wood Modification*. Cardiff, UK, pp. 431-438.

Bongers, H.P.M. and E.P.J. Beckers. (2003). Mechanical properties of acetylated solid wood treated on pilot plant scale. In: *Proceedings of the First European Conference on Wood Modification*. Ghent, Belgium, pp. 341-351.

Bongers, F., Roberts, M., Stebbins, H. and R. Rowell (2009). Introduction of Accoya® wood on the market – technical aspects. In: *Proceedings of the Forth European Conference on Wood Modification*. Stockholm, Sweden, pp. 301-310.

Boonstra, M.J., Van Acker, J., Tjeerdsma, B.F. and E.V. Kegel (2007). Strength properties of thermally modified softwoods and its relatio to polymeric structural wood constituents. *Annals of Forest Science*, **64**, 679-690.

BRL 0605 (2003). *National assessment directive for the KOMO® product certificate Modified Timber.* Certification and Attestation body SKH, Wageningen, the Netherlands.

Dreher, W.A., Goldstein, I.S. and G.R. Cramer (1964). Mechanical properties of acetylated wood. *Forest Products Journal*, **14**(2), 66-68.

Epmeier, H., Johansson, M., Kliger, R. and M. Westin (2007a). Material properties and their interrelation in chemically modified clear wood of Scots pine. *Holzforschung* **61**, 34-42.

Epmeier, H., Johansson, M., Kliger, R. and M. Westin (2007b). Bending creep performance of modified wood. *Holz als Roh- und Werkstoff*, **65**, 343-351.

Homan, W. and B. Tjeerdsma (2005). Control systems, quality assessment and certification of modified wood for marked introduction. In: *Proceedings of the Second European Conference on Wood Modification*. Göttingen, Germany, pp. 382-389.

Hill, C.A.S. (2006). Wood modification: chemical, thermal and other Processes. John Wiley & Sons, Chichester, England, 239 pp.

Homan, W. and A. Jorissen (2004). Wood Modification Developments. *Heron*, **49**(4), 361-386.

Jones, D. (2007). The Commercialisation of Wood Modification – Past, Present and Future. In: *Proceedings of the Third European Conference on Wood Modification*. Cardiff, UK, pp. 439-446.

Jorissen, A., Bongers, F., Kattenbroek, B. and W. Homan (2005). The influence of acetylation of radiata pine in structural sizes on its strength properties. In: *Proceedings of the Second European Conference on Wood Modification*. Göttingen, Germany, p. 108-115.

Jorissen, A. and E. Lüning (2010). Wood modification in relation to bridge design in the Netherlands. In: *Proceedings of 11th World Conference on Timber Engineering*. Riva del Garda, Trentino, Italy.

Kattenbroek, B. (2005). How to introduce acetylated wood from the first commercial production into Europe. In: *Proceedings of the Second European Conference on Wood Modification.* Göttingen, Germany, pp. 398-403.

Lawrence, A. (2008). Timber bridges, an international perspective. *The Structural Engineer* 16 September 2008, 26-31.

Larsson, P. and R. Simonson (1994) A study of strength, hardness and deformation of acetylated Scandinavian softwoods. *Holz als Roh- und Werkstoff*, **52**, 83-86.

Norimoto, M., Gril, J. and R.M. Rowell (1992). Rheological properties of chemically modified wood. Relationship between dimensional stability and creep stability. *Wood Fiber Science*, **24**(1), 25-35.

Rowell, R.M. (2006). Chemical modification of wood: A journey from analytical technique to commercial reality. *Forest Products Journal*, **56**(9), 4-12.

Rowell R.M. (1996). Physical and mechanical properties of chemically modified wood. In: *Chemical Modification of Lignocellulosic Materials*. Hon, D.N.S. (Ed.), Marcel Dekker, New York, USA, pp. 295-310.

Rowell, R.M., Ibach, R.E., McSweeny, J. and Nilsson, T. (2009). Understanding Decay Resistance, Dimensional Stability and Strength Changes in Heat Treated and Acetylated Wood.. In: *Proceedings of the Forth European Conference on Wood Modification*. Stockholm, Sweden, pp. 489-502.

SKH Publicatie 97-04 (2006). Beoordelingsgrondslag Houtsoorten voor toepassing in timmerwerk; eisen en bepalingsmethoden. *Certification and Attestation body SKH*, Wageningen, the Netherlands.

Tjeerdsma, B., Kattenbroek, B., Jorissen, A. (2007). Acetylated wood in exterior and heavy load-bearing constructions. Building of two timber traffic bridges of acetylated radiata pine. In: *Proceedings of the Third European Conference on Wood Modification*. Cardiff, Wales, UK,. pp. 403-411.

Tjeerdsma, B. and F. Bongers (2009). The making of: a traffic timber bridge of acetylated Radiata pine. In: *Proceedings of the Forth European Conference on Wood Modification*. Stockholm, Sweden, pp. 15-22.

Van der Lugt P., Lüning, E., Purse, L., Adair, C. and H. Stebbins (2010). Carbon Footprint Assessment for Acetylated Wood Applications. *Paper submitted for the Fifth European Conference on Wood Modification.* Riga, Latvia.

VFF Merkblatt HO.06-4 (2010). Holzarten für den Fensterbau – Teil 4: Modifizierte Hölzer. *Verband der Fenster- und Fassadenhersteller e.V., Gütegemeinschaft Fenster und -Haustüren e.V.*, Germany.

Vick, C.B. and R.M. Rowell (1990). Adhesive bonding of acetylated wood. *International Journal of Adhesion and Adhesives*, **10**(4), 263-272.

Widmann, R (2009). Thermally modified beech as a structural material: Allocation to European strength-classes and relevant grading procedures. In: *Proceedings of the Forth European Conference on Wood Modification*. Stockholm, Sweden, pp. 379-386.

Winandy, J.E. and R.M. Rowell (1984). The chemistry of wood strength. In: *The Chemistry of solid wood*. Rowell, R.M. (Ed), American Chemical Society, Washington, DC, USA, pp. 211-256.