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REVIEW

Review on antibacterial biocomposites of structural laminated veneer lumber

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Abstract In this review, the characteristics and applications of structural laminated veneer lumber made from planted forest wood is introduced, and its preparation is explained, including various tree species and slab qualities, treatments for multiple effects and reinforced composites. The relevant factors in the bonding technology and pressing processes as well as the mechanical properties, research direction and application prospects of structural laminated veneer lumber made from planted forest wood are discussed.

Contents

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1. Introduction

The planted forests in China already cover an area of 800 million acres, though plantation wood has yet provided little benefit in the long run for the current backward process technology. With the rapid development of the Chinese economy, however, construction of timber structures such as homes and bridges calls for a large amount of engineered materials for wooden structures (Tenorio et al., 2011). There is, therefore, a huge potential for plantation wood to produce high value-added wood composite engineered materials on a large scale owing to its fast growth, low price and good shape (Peng et al., 2015). High-end products from wood composite engineered materials for wood structures provide an important means to process and use plantation wood efficiently. Engineered materials for wood structures with high additional value are primarily made by gluing and laminating wood (Rasheed et al., 2015). Plantation wood as-harvested cannot typically be applied to heavy timber construction because of its uncertain material quality, which limits its load bearing capacity. Moreover, plantation wood used as-harvested is apt to decay and burn and outdoor conditions can speed up its aging, splitting and deformation can occur, and its service life can be shortened, reducing its already low usage value and impairing its engineering safety. The most cost-effective way to manufacture engineered materials for wood structures is from laminated veneer lumber, where the material properties of fast-growing plantation wood are synthetically considered (Sultana et al., 2015).

Laminated veneer lumber (LVL) is a high-performance product that is made by splicing and pressing multilayer rift grain veneer (or cross-grain veneer) from thick rotary-cut veneer. Laminated veneer lumber is often divided into the two categories of structural and non-structural use, where structural LVL is used in the high-bearing-capacity field and non-structural LVL is applied to areas protected from loads or which require a low carrying capacity (Qureshi et al., 2015). The process procedure for LVL includes log truncating, log steaming, log skinning, veneer peeling, veneer clipping, veneer drying, veneer scarf-jointing, veneer blending, laying up, prepressing, hot pressing, sawing, stacking, checking and packaging (Özçifçi, 2009).

2. Applications

Structural LVL is presently one of the fastest growing wood-based groups in North America, where 61% of structural LVL is used for I-shaped floor joists and 31% is used as trusses and beam-columns, while the rest is used for sleeper and load-bearing walls. Research on LVL in the architectural field has reached the large-scale industrialization level, especially in countries such as the United States of America, Japan and Canada. In these countries, the USA is the largest producer and consumer of structural LVL around the world with six companies manufacturing construction-grade LVL. There are three firms producing structural LVL in Canada, while Japan has four full sets of product lines and a production capacity about twice that of Canada. The annual production of LVL in China is presently about two million cubic meters, (Nasreen et al., 2015) the production and application of which remains limited to non-structural use in low value-added fields such as furniture and interior applications. With the large-scale development of wood structures in China, however, there is an increasing demand for structural LVL (Javed et al., 2015).

3. Characteristics

There are many advantages of construction-grade LVL. First, natural flaws such as gnarls, cracks and cross-grains generally existing in sawn timber are distributed at random over the veneers, causing its strength to be uniform. Second, the dimensions of construction-grade LVL are not limited by the size of the log and its resulting veneer because of the special production method, where the product dimensions are flexible and may be freely chosen (Hashemi et al., 2015). Third, warpage and distortion are less likely to occur in the laminated structure, leading to enhanced stability. Fourth, the processing of construction-grade LVL is convenient, and it can be sawn, sliced, drilled and mortised in the same fashion as wood. Fifth, the shock resistance of constructional LVL is strong and can resist the fatigue rupture that can arise from cyclic stress. Sixth, the timeliness of wood pyrolysis and the glued structure of LVL create a flame resistance superior to that of steel. Seventh, construction-grade LVL is made by laminating and gluing veneer with waterproof adhesive, making its weather resistance higher than that of other wood materials (Mateen et al., 2015).

4. Antibacterial preparation

4.1. Tree species and slab qualities

Timber resources are the key raw materials for wood-based panels and determine the properties thereof, and there has been much research exploring the feasibility of manufacturing LVL using different types of materials. For instance, Ozarska has confirmed that laminated wood and LVL could be produced by replacing hardwood with eucalyptus after comparison of the properties of the two different kinds of wood (Ozarska, 1999). Mathieu et al. took advantage of blackbutt (*Eucalyptus pilularis*) to prepare LVL whose bonding strength met the performance requirements for durable structural materials (Mathieu et al., 2004). De Souza et al. have tested the physical properties and biological performances of LVL using *Pinus oocarpa* and *Pinus kesiya* veneers as raw materials and have shown that, though both types of boards have broad prospects for development, the mechanical properties of *P. kesiya* LVL are higher than those of *P. oocarpa* LVL (De Souza et al., 2011). In 2004, Aydın et al. used comparative tests to find that the physical and mechanical properties of LVL made of beech and eucalyptus varied drastically by tree species (Aydın et al., 2004), a comparative study on some physical and mechanical properties. Later, Chen and Zhang pointed out that the main raw materials for manufacturing LVL in North America were medium- or low-density tree species of which 95% were softwoods, primarily pine and fir (*Abies*) in North America and *Araucaria cunninghamii* in Chile (Chen and Zhang, 2012). Moreover, researchers in Japan have presented deep and meticulous reports on the development of high-performance composite materials using bamboo as the raw material. In China, scholars have chiefly taken plantation wood or bamboo as the raw material to manufacture LVL. Yu et al. have explored the manufacturing process and main performance of LVL made of eucalyptus (Yu et al., 2012). Long and Wei (2005) have obtained an optimal hot pressing process using rotary cut paulownia veneer and a urea formaldehyde resin adhesive to produce paulownia LVL. Xu et al. have studied the entire process technology of small-caliber Chinese fir by preprocessing, veneer peeling, veneer drying, lengthwise jointing of the veneer, gluing and hot pressing in sequence, and have ultimately indicated that it was feasible to use fast-growing Chinese fir to prepare LVL (Xu et al., 2010). The optimum process conditions used in this experimental research were a hot pressing temperature of 165 °C, a hot pressing time of 1.20 min/mm and a single glue layer spread of 200 g/m^2. Zhang et al. have researched the production of dimensioning larch LVL to satisfy the requirements for timber construction using laminated wood production equipment, and tested and evaluated the relevant properties (Zhang et al., 2005). Bao and Fu have investigated the contribution of the properties of poplar wood to the strength of LVL, and have proposed the concept of a contribution rate to measure the solid wood properties' contribution to the strength of LVL (Bao and Fu, 1999).

4.2. Treatments for multiple effects and reinforced composites

Laminated veneer lumber used in various fields, and especially in engineered materials for timber structures, must meet certain mechanical strength requirements and have superior endurance characteristics and safety performances (Batool et al., 2015). To this end, researchers have treated LVL for multiple effects, such as corrosion protection and flame retardation, and have reinforced LVL using laminated composites made of a variety of reinforced materials. As a preservative treatment, Jin et al. have impregnated poplar veneer with alkaline copper quaternary (ACQ) under atmospheric pressure and subsequently pressed the treated poplar veneer into LVL, also testing and analyzing the impact of the preservative load capacity upon the physical properties of the LVL (Jin et al., 2012). As a flame retardation treatment, Xiao et al. have used thinned Chinese fir wood impregnated with a fire resistant liquid to produce flame-retardant LVL whose physical properties, while meeting the Japan Agricultural Standards (JAS) for laminated wood, also exhibited the effect of flame retardation, making it eligible for use in interior and furniture design (Xiao et al., 2013). With reference to enhancement processing, Liu et al. have prepared solid-type poplar LVL using the impregnation method and low-molecular-weight phenolic resin, whereupon the effect of different impregnation methods and impregnation increments upon the mechanical properties was explored, and the reinforced LVL was thereby optimized to meet structural material standards (Liu et al., 2008). With reference to the integration process, Zhang et al. have investigated both the dyeing process and the fire retardation treatment with Chinese white poplar veneer using the orthogonal experiment method, where they studied a hot-press gluing experiment on the LVL to determine the process synchronization for dyeing, anti-combustion and the hot-press technology (Zhang et al., 2005). There has also been much research on laminated composites with reinforced materials, which mainly uses different wood species or non-timber materials together with wood. To study laminated composites with different wood species, Hsu has proposed for the first time a method to produce LVL using veneers of different wood species, and has shown that the strength of the LVL produced by compositing a high-density birch veneer as the top layer and a poplar veneer as the core layer improved significantly compared with the poplar LVL (Hsu, 1988). To modify the structure of the thin-type LVL, Xu and Hua have joined the veneer transversely in LVL and took the approach of compositing veneer and fiber board to improve the horizontal sweeping of LVL that results from laying up with the grain (Xu and Hua, 2002). The results indicated that the bending resistance of the LVL decreased somewhat and its dimension stability improved significantly, while the elastic modulus and bending strength both fulfilled the national standard requirements by inserting the veneer laterally. However, this method for compositing the veneer and the fiber board was not appropriate for improving the product performance because of the reduction in internal bonding strength. A laminated composite of non-timber materials and wood was studied by Madhoushi and Ansell who glued glass fiber reinforced plastic (GFRP) pultruded rods and LVL together using epoxide resin at room temperature to study the tensile fatigue strength (Madhoushi and Ansell, 2004). On the one hand, Wang et al. have researched the performance of laminated boards produced using different metal materials and various metal mesh specifications under different lay-up conditions, where it was shown that the wire net produced a significant strengthening effect upon the elastic modulus and the bending strength of poplar LVL, where the mesh size was the key factor affecting the performance criteria of the bonding strength, modulus of elasticity and modulus of rupture (Wang et al., 2003). On the other hand, Cheng and Huang have manufactured LVL by compositing glass fiber and poplar veneer to explore its impact upon flexural properties, where the experimental results demonstrated that glass fiber had a significant strengthening effect upon the longitudinal elastic modulus and the bending strength of the poplar LVL, and its lateral performance was also enhanced significantly (Cheng and Huang, 2008). In addition, Li et al. have used carbon fiber reinforced plastic (CFRP) to reinforce wood beams made of poplar LVL, wherein the research indicated that the stiffness and maximum failure load improved dramatically with CFRP reinforcement (Li et al., 2009).

4.3. Factors in the bonding technology and pressing processes

The bonding strength and mechanical properties of LVL are subject to the pressing process and other factors present in the bonding technology such as selection of glue species, method of gluing and amount of spread, and has been a focus of research for many scholars. To explore the factors present in the bonding technology, Bridaux et al. have manufactured LVL by adding boric acid to melamine resin adhesive, and found the durability of LVL was increased after the test by virtue of the combination of boric acid and the adhesive (Bridaux et al., 2001). Uysal, has produced pine and Chinese fir LVL vapor treated using phenol-formaldehyde, poly(vinyl acetate), desmodur-VTKA and urea-formaldehyde, exploring the bonding strength and dimension stability of the LVL (Uysal, 2005). Wang et al. have discussed the gluing of wire mesh and poplar veneer when phenolic resin, epoxy resin and polyurethane resin were used for preparing poplar LVL reinforced with metal (Wang et al., 2013). Liu et al. have taken urea-formaldehyde modified with melamine as the adhesive and used the response surface method and a central composite rotatable design to optimize the processing technology conditions for eucalyptus LVL (Liu et al., 2009). Meng et al. have analyzed the impact of the resin solid content upon the mechanical properties and water resistance of LVL made using fibrosis bamboo veneer, where the experimental results showed that with an increasing resin solid content, the flexural strength and tensile strength of the board were decreased, the water resistance and horizontal shear strength were increased, and there was an insignificant change in the flexural modulus and compression strength (Meng et al., 2011). While studying the pressing process, Troughton and Lum found that LVL made via steam injection pressing possessed excellent bonding strength (Troughton and Lum, 2000). Yu, obtained the optimum technology of structural LVL produced by cold pressing of fast-growing poplar with resorcinol resin adhesive, with optimum values found to be 0.98 MPa for the specific pressure, 7 h for the pressure time, 40 min for the assembly time and 180 g/m^2 for the amount of glue (Yu, 2012). The performance of the LVL manufactured in this way was higher than that required by the Japanese Agricultural Standards when the curing time exceeded 7 h. Chen and Xu have explored the possibility of preparing the LVL using small-diameter plantation wood of Chinese fir, and systematically analyzed the relationship between the physical and mechanical properties and the three hot pressing factors of temperature, time and pressure to gain the optimal process for Chinese fir LVL produced in laboratories (Chen and Xu, 2000). Deng et al. used bamboo (*Neosinocalamus affinis*) as a main research object and evaluated the fiber elements in fibrosis bamboo veneer, wherein laminated veneer lumber made of fibrosis bamboo veneers possessing different densities was manufactured using different hot pressing temperatures and rates of glue spreading, and the effect of the pressing process upon the physical properties was also analyzed (Deng et al., 2008).

4.4. Mechanical properties

For application, it is fundamental to study the mechanical properties of LVL as a structural material. Xu and Jin have researched the creep property, elastic modulus and static bending strength of LVL and have shown that its creep property curve was similar to that of wood (Xu and Jin, 2001). Huang et al. have tested the longitudinal modulus of elasticity and the length and breadth Poisson ratios of a high-frequency and thermal pressure technology-based thick poplar LVL built upon the four-point bending method (Huang et al., 2013). The test results indicated that the longitudinal modulus of elasticity of the poplar LVL was close to or even above that of poplar veneer, offering a certain reference value for materials introduced to the field of heavy packing boxes and a structural material that can substitute for wood. Yu et al. have manufactured LVL using veneers of *N. affinis* bamboo ties and phenolic resin, and studied the hygroscopic properties and the changes in the flexural property and compression performance in the hot and humid process by moisture soak at the temperatures 20, 36 and 60 °C (Yu et al., 2007). Xue and Hu have analyzed the mechanical properties of LVL made of poplar and birch by means of composite material mechanics and computer simulation, and have found that the theoretical results for the elastic modulus and static bending strength are very close to those found by finite element analysis (Xue and Hu, 2012), where the maximum relative error between the two results is no more than 5% wood extractives could reduce mechanical properties (Khan et al., 2015; Khaskheli et al., 2015). Many studies have been made using molecular identification methods to understand the chemical composition of many woody extracts and biomasses (Peng et al., 2011, 2012a,b,c). The research results are very effective and carry great reference value (Peng et al., 2013a,b,c, 2014a,b). Also in 2012, Franke and Quenneville investigated the failure types of fracture model I, fracture model II and the mixed mode found in *Pinus radiata* timber and in LVL in New Zealand, finding that the toughness of the latter is higher than that of the former (Franke and Quenneville, 2012).

5. Conclusions

It can be seen from this review that scholars in China and elsewhere have performed extensive research on LVL in terms of the various tree species and slab qualities, treatments for multiple effects and reinforced composites, factors in bonding technology and pressing processes as well as mechanical properties, making great contributions to the rapid growth in the understanding of LVL, while also affording a powerful guarantee of the application of LVL in various fields.

With the constant decline in the availability of quality wood, the manufacture of LVL from fast-growing plantation wood is an area that deserves to be taken seriously, and large-sized structural LVL for use in buildings and bridges will continue to play an important role in the market. To improve its mechanical strength, endurance characteristics and safety performance, research has mainly focused on a single modified treatment for LVL; including corrosion resistance, flame retardation and performance reinforcement. A crucial issue for scholars to resolve in the future is to develop integrated processes to produce multiple effects, performance reinforcement and laminated composites.

It is currently quite important to research factors in bonding technology and pressing processes for LVL, and valuable research results have been achieved. Although there have been studies on the failure modes and damage mechanisms of LVL, further study is necessary to fully understand the forms leading to destruction and the simulation analysis of LVL created with strengthened and laminated composites.

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