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Delamination detection in wood – based composites, a methodological review.

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ABSTRACT

Commonly observed damage in wood products and wood-based composites are: wood fibre fracture, delamination between plies or debonding of wood–adhesive layers. Delamination which is probably the most frequently observed damage, may be produced during manufacturing or, during in service loading such as accidental excessive loading produced for example by snow or, by fatigue in highly variable environmental conditions of temperature and humidity. Damage detection in general and delamination in particular is a very important issue in the context of structural health monitoring for mechanical engineering infrastructure with elements in wood and wood-based composites. The development of computational techniques in the last twenty five years, and the progress achieved in mechanical characterisation of solids in general and of composites in particular, affected positively the development of the modelling of wood and wood-based composites mechanical behaviour. Related studies clearly suggest that delamination in solid wood can occur between different layers of the cell wall at submicroscopic, microscopic and macroscopic structural levels. With respect to wood-based composites, the behaviour of two groups of products has been analysed: the laminated products and the fibre–based products. Delamination detection studies were summarized in the context of structural health monitoring, The review of the theoretical aspects related to the detection of damages induced by delamination in composites was oriented in two main directions: the nondestructive evaluation method using an ultrasonic technique with Lamb waves, which is an experimental method able to provide local damage information and the model dependent method, at relatively low frequency, which undertake analysis of structural models implemented by finite element analysis and is able to provide global damage information, for linear and non-linear mechanical behavior of the system The development of wood – based composites testing methodologies for delamination detection should be encouraged as part of the efforts being made to control the performance of low cost building materials

1. Introduction

Mechanical integrity of interfaces in wood-based composites plays a major role in determining the serviceability of structures and their components. New advanced materials (i.e parallel-strand lumber, laminated veneer lumber, etc.) are designed with specialty interfaces to increase fracture resistance of wood-based composite materials and to accommodate residual stresses. Of particular note is the fact that the mechanical properties of wood–based composites, used mainly in civil engineering, may degrade severely in the presence of damage, often with tragic consequences. Therefore damage detection is a very important issue in the context of structural health monitoring for mechanical engineering infrastructure with elements in wood and wood-based composites.

Wood-based composites are complex materials exhibiting important anisotropic properties. Commonly observed damage in these materials are: delamination between plies, debonding of wood–adhesive layers, and wood fibre fracture. Delamination in wood can occur at macroscopic, microscopic and submicroscopic scales in wood components. (Bucur 2010) Delamination in wood-based composites may result from manufacturing errors, by imperfecte bonding, by separation of adjoining piles, etc., or, during in service loading such as by accidentally excessive loading produced for example by snow or, by fatigue in cyclical environmental conditions of temperature and humidity.

The prediction of delamination in composites (Hanagud et al 1990, 1992, Tay 2003, Sridharan 2008) is a challenge for both scientists and manufacturers. This is due to the large number of parameters involved in the design of composites and, on the other hand, to the complexity of the stress state which leads to the initiation and propagation of delamination.

For delamination initiation aspect, the tolerance prediction is based on semi-empirical criteria, such as point–stress or average stress criteria. Due to the use of such criteria, industries perform numerous tests in order to ensure the safety margins for delamination failure are not exceeded. The non-propagation certification relies on fracture mechanics analyses, which are very complex and introduce difficulties for the characterization of the initial delamination pattern (Srinivasan 1996, Murata and Masuda 2006).

In the last thirty years there have been several important advances toward a better understanding of the mechanics of laminated composites and of the damage mechanisms, because of their intensive utilisation in aerospace engineering. This progress concerns the analysis and identification on the micro, macro and meso scales, as well as the development of advanced anisotropic material models. To be able to rely on computational models, both academics and manufacturers recognize that a prerequisite is to develop a detailed material model with a clear identification procedure and to validate this model by means of representative experimental tests.

The physics of delamination is governed by interactions among different damage mechanisms, such as fibre breakage, transverse microcracking and debonding of the adjacent layers of the cell wall. To understand the physics of delamination in composite biological materials and more specifically in wood, wood based products and wood-based composites, it is necessary to have detailed knowledge about the microstructure of these materials.

As noted by Kelly (1989) in the Concise Encyclopedia of Composite Materials, “plant cells are a good example of laminated composite material; the shape of the cells is roughly tubular with various laminae of cellulose microfibrils glued together to form a wall. Each lamina has a characteristic fibre orientation which can be random, cross-helical or single – helical. These biomaterials are grown under stress; this means that the loading conditions of the structure as a whole can be used effectively as blueprints for the most efficient use of fibre reinforcement. By their very nature, natural fibrous composites are better materials in tension than in compression and their use in many applications is often limited by this fact. The excess of tensile strength available can be profitably used to pre-stress in tension the regions of the structure which are more vulnerable to compressive loads. Also the presence of water as compression members will result in lighter structures”.

2 Wood material

Wood is a natural fibrous, layered composite which exhibits a remarkable combination of properties related to strength, stiffness and toughness. The mechanical properties of this material can be represented commonly by an orthotropic or transverse isotropic structure or by a much more sophisticated monoclinic structure (Bucur and Rasolofosaon 1998, Bucur 2003).

Several models have been proposed to represent wood structure in relation to its mechanical behaviour such as:

a) - an array of parallel cylindrical tubes, of isotropic structure, oriented in the stem direction. (Price 1928, Srinivasan 1996, Barlow 1997)

b) - a matrix and framework. The corresponding mechanical properties of the cell wall material can be derived from the natural polymer constituent (cellulose, hemicellulose and lignin) properties by the rule of mixture (Mark 1967)

c) - cellular structure model with hexagonal cell shape, for which the principles of cellular solid mechanics are used. Some improvements of this approach were given by Kahle and Woodhouse (1994) and Watanabe et al (2000, 2002), who considered the cell wall material as transversely isotropic.

d) - multiscale models, using three-dimensional finite element simulation of representative softwood related cellular models. Data related to the microstructural characteristics such as the micrifibril angle and the chemical composition of the cell wall such as lignin, hemicelluloses, water and crystalline cellulose were also integrated into their models (Harrington et al. 1998, Astley et al. 1998, Yamamoto 1999, Persson 2000, Watanabe and Norimoto 2000, Yamamoto et al. 2005, Hofstetter et al. 2005, 2006, Fritsch and Hellmich 2007).

e) -model considering simultaneously the continuum mechanics for the solid–type behaviour of the cell wall and on the other hand, the unit cell method, for the plate-type behaviour of the softwood microstructure (Hofstetter et al. (2007). It was stated that the activation of different load–carrying mechanisms of cellular structure depends on the loading state of wood, such as for example:

- the plate-type bending and shear deformations of the cell walls which are dominant in the tangential direction, when the transverse shear loading and longitudinal compression straining are applied on solid wood specimens.
- the solid-type deformations are dominant in longitudinal and radial directions when longitudinal shearing loading straining are induced on wood specimens.

At a cellular scale the plate–like deformation modes were studied combining random/periodic multi-step homogenisation with corresponding values obtained from continuum micromechanics modeling. The average predictive capacity of this model is low, about 8%, with very large variations depending on the value of the elastic constants. The highest errors were observed on G_{RT} (error can be as high as 290%) and on Poisson’s ratios (error of about 75%).

It is very likely that the predictive capacity of this model could be substantially improved by using more accurate values of the elastic constants at a microscopic scale, which can be obtained with the development of specific acoustic microscopic technique as suggested by Bucur (2003).

All these studies cited previously and related to the modelling of wood structure clearly suggest that delamination can occur between different layers at submicroscopic, microscopic and macroscopic structural levels.

3. Wood-based composites

With regards to the wood-based composites, the mechanical behaviour of two groups of products could be analysed: the *laminated* wood products and *the fibre–based* products.

Performance criteria for wood-based composites relate directly to product end use. *Laminated* products are frequently used for structural purposes. This requires consideration of engineering strength needs, safety and short and long term response of the material to the service environment. Structural, exterior–grade products have the most demanding bond-quality requirements, since glue line failure could be catastrophic to these structures. In these situations glue line strength, durability and reliability must be assured, by computational analysis and bond quality testing programs. Computational models to simulate mechanical behaviour of new wood-based composites are critically needed because of cost-effectiveness. The effects of varying raw material characteristics on the mechanical properties of prospective new products can be thoroughly analysed. The intensive and expensive bond quality testing programs also can be improved by modeling. Finite element modelling of laminated wood composites as a multilayer system was proposed (Triche and Hunt 1993, Wu et al 2004) for predicting tensile, compression or bending strength and stiffness using failure criteria. Clouston and Lam (2001, 2002) and Clouston (2007) proposed an advanced methodology for analysing the multiaxial stress states in small specimens of parallel wood-strand composites, using a 3D non-linear stochastic finite element model and Monte Carlo simulations. The Tsai-Wu strength theory to predict the ultimate load carrying capacity of a centre point off-axis bending member made from Douglas fir laminated veneer, incorporating the size effect was reported by Clouston et al. (1998).

References relating to the modelling of mechanical behaviour of fibre-based composites are as abundant as those for laminated wood-based composites (Smulski and Ifju 1987, Chakraborty et al. 2006). Mechanical properties of fibre-based composites are influenced by factors such as: fibre geometry, orientation and distribution, fibres packing in flake of different orientation, random distribution of flakes, moisture content, adhesive–type, etc. Single layer flake models and multilayer mat structures were suggested (Bodig and Jayne 1982, Steiner and Dai 1993, Dai and Steiner1994, Lenth and Kamke 1996) to explain the mechanical behaviour of fibre based composites. Several authors (Ogawa 2000, Tascioglu et al 2003,) reported successful utilisation of hybrid fiber–reinforced polymer composites – glulam products for structural applications in civil infrastructures such as beams for bridges stringers, panels for bridge and pier decks. It was noted that these composites are very resistant to delamination tests during accelerated exposure to wetting and drying (Pirvu et al. 2004). Mechanical defibering action produces important structural modifications such as: internal fibrillation observed as a helical wraps of fibres, cell wall delamination, external fibrillation which is the peeling off of the fibrils from the fibre surface, with formation of fines, fibrils or fibrillar lamellae attached to the exterior fibre surface and fibre shortening, depending on the refining conditions, the fibre type – hardwood or softwood- and the pulp type – mechanical or chemical. It is appropriate to mention here that the hydroxyl groups available on the surface of the cellulose molecule are the prime means by which fibres and cement, or other material used as matrix, bond together (Coutts 2005). The increasing environmental concern about the wastes from wood, wood products, forest waste and construction waste materials has given rise to the development of new or improved technological processes such as the water–vapour explosion process. This process rapidly defibrates wood wastes producing a new raw material for novel wood cement composites (Wei et al 2004).

4. Vibration – based approach for delamination detection

Delamination in composites can be revealed by vibration-based techniques and can be related to the local and global damage detection. The local damage detection is performed with an ultrasonic technique (Lamb waves, etc) while the global damage detection is based on a model – based method using low frequency vibrations and undertaking the analysis of structural models implemented by finite element analysis or other more complex techniques.

4.1 Ultrasonic techniques

Interfaces play an important role in determining the performance of laminated composite materials on a wide variety of scales, from interlaminar bonds to adhesive bonds. The defects expected to be present at the interface are cracks at the interfaces of different oriented plies, inter-ply delamination, adhesion weakness at interfaces between plies or between a ply and an adhesive layer. In all cases the basic purpose of the nondestructive evaluation methods is the determination of the integrity of bonds (Potel and de Belleval 1993a, b, Hosten et al 1987, Su et al 2002, Sohn et al 2004, Sohn et al 2003). The efficiency of ultrasonic methods is related to the understanding of the relationship between the measured parameters and the interface mechanical properties, which is dependent on the theoretical approach used to predict the behavior of the interface, according to the specific kind of defect expected to be present Combining the experimental data with the theoretical knowledge (Hirsekorn 2001) it is possible to gain important information about the linear or non linear interface behavior (Krohn et al. 2002, Solodov et al. 2002).

4.2 Low frequency techniques

Compared with ultrasonic nondestructive testing and evaluation procedures, the model-based methods using low frequency vibrations have a more rigorous mathematical background, but also several limitations related to the interpretation of the physical meanings of the detected results and the precise numerical representation of the structures. The mechanical behavior of a damaged structure can be studied in two hypotheses, the linear or the non linear mechanical behavior. In that follows both aspects will be succinctly described.

4.2.1 Linear behavior

Model – based methods implemented by finite element analysis under static or dynamic loading, assume that the linear monitored structure responds can be accurately described by finite element analysis. It is assumed that the behavior of the structure is *linear* before and after damage. The composites are usually modeled as beams (Euler beam, Timoshenko beam) with through-width delaminations parallel to the beam surface located arbitrarily, or shells.

Kim et al. (1997) proposed an analytical solution for predicting delamination buckling and growth of a thin fiber reinforced plastic layer in laminated wood beams under static bending. It was noted that delamination growth is related to an explicit form of strain-energy release rate and that the critical load can be accurately predicted. Simulation of the delamination indicated an unstable growth of the delamination after buckling of the delaminated sub-laminate, followed by arrested delamination growth.

For the vibrating beams, the foundation of linear analysis is based on the concept of linear normal mode and the principle of superimposition. Linear normal modes are synchronous harmonic particular solutions of the homogeneous linear system (Vakakis 1996).

The dynamic model - based methods use changes in vibrational modal properties (i.e. modal frequencies, modal damping values and mode shapes) to infer changes in mechanical properties of the structure. The impulse or continuous excitation techniques can be used for vibrating the structure. Commonly a hammer technique is used for impulse excitation.

The utilization of a non-contact scanning laser vibrometer system allows acquisition of a large number of measurement points for a better definition of the mode shapes. Continuous sine excitation can be produced by using PZT – lead-zirconate-titanate - ceramic wafers as actuator.

The dynamic model – dependent methods can be subdivided into: modal analysis, frequency domain, time domain and impedance domain, according to the dynamic response parameters analyzed. Frequencies, mode shapes, curvature mode shapes and modal damping, which are function of the physical properties of the structure (mass, damping and stiffness), are the most commonly measured parameters, when the dynamic model - based methods are used.

Modification of physical properties of the structure, such as for example reduction of stiffness resulting from cracks or delamination, will implicitly cause detectable changes in modal parameters. Furthermore, these changes must be used as indicators of damage, and the process of vibration - based damage detection reduced to some form of pattern recognition problem, as can be seen from the references cited below and extracted from a huge literature, from which some references are selected (Adams et al. 1978, Cawley 1990, Cawley and Adams 1979, 1987, Wang et al. 1982, Tracy and Pardoen 1989, Nagesh and Hanagud 1990, Paolozi and Peroni 1990, Petyt 1990, Hanagud et al. 1990, 1992, Pandey et al. 1991, Tenek et al. 1993, Luo and Hanagud 1996, Messina et al. 1998, Sampaio et al. 1999, Wahl 1999, Lestari and Hanagud 1999, D'Ambrogio and Fregolent 2000, Brandinelli and Massabo 2002, Kessler et al. 2002, Lee et al. 2003, Berthelot and Sefrani 2004, Chrysochoidis and Saravanos 2004, Della and Shu 2005, Ghoshal 2005, Coutellier et al. 2006, de Borst and Remmers 2006, Ladevèze et al. 2006, Lestari et al. 2007,).

Because of the fact that the damage is a typical local phenomenon, several difficulties can arise in its detection and location such as:

- higher frequency modes are able to capture local responses, whereas lower frequency modes capture the global response of the structure
- for the excitation of higher modes more energy is required than for the excitation of lower modes and loss of information can result from the reduction of time history measurements
- shifting from the linear to nonlinear response.

For damage identification and health monitoring of structures, many different issues are critical, such as: the excitation and measurement configurations, the selection of the type of sensors and their location, the signal processing performing such as : Fast Fourier analysis, time – frequency analysis, or wavelet analysis (Castro et al. 2007).

4.2.2 Nonlinear behaviour

Nonlinear damage is observed in the case when the initially linear-elastic structure behaves nonlinearly after the damage has been produced. Nonlinear normal modes are defined as some synchronous periodic particular solutions of the homogeneous nonlinear system under which all degrees of freedom undergo the extreme position at the same time (Vakakis 1996).

The most frequent nonlinearities in a delaminated beam are introduced by: the nonlinear geometric effects such as axial stretch effects, the deflection – dependent interactions in both longitudinal and transverse directions, the intermittent contacts between the segments during vibration, the delaminated segments constraining the movement of each other or the growth of delamination.

Another group of methods used for the implementation of nonparametric- models methods and based on the identification of the nonlinear response of the structure are the neural-network-based methods (Luo and Hanagud 1997).

Prognosis with statistical model development for feature discrimination is also a group of methods recently developed for structural health monitoring and damage detection (Montalvao et al 2006, Wang and He 2007).

4.2.3. Some practical aspects

As noted by Sohn et al. (2003) the implementation of a structural health monitoring systems must answer questions, related to the presence of damage and to the operational evaluation, such as:

- the damage detection (existence of damage in the system), the damage location (where is the damage), the type of damage (what kind of damage), the extent of damage (how severe is the damage) and the prognosis (how much useful life remains).

- the operational and the environmental condition which referes to the safety and economic motivations for performing the monitoring, and on the other hand which are the limitation on acquiring data.

The structural health monitoring process of big wood laminated structures, in light of normal aging and degradation resulting from operational environments, must involve the periodic inspection of the system using:

- sampled dynamic response measurements from an array of transducers, establishing their number, resolution, bandwidth, data acquisition (periodically or continuously), storage and transmittal hardware;
- extraction of the damage – sensitive features, normalization of data by the measured inputs or by environmental cycles (summer, winter) ;
- statistical analysis of data to determine the current state of the system.

After catastrophic events such as earthquakes, excessive snow loading, etc, the structural health monitoring process must provide reliable information about the integrity of the structure.

5. Conclusion

The review of the theoretical ideas was done in order to perceive and identify for the future, the research directions able to identify the damage detection induced by delamination in wood products and in wood-based composites using ultrasonic and low-frequency vibration measurements, for a practical implemented technology. This imply three main aspects : the understanding of the theoretical aspects related to the physical phenomena for delamination initiation and growth , the development of models and testing procedures, and the developments and validation of specific codes. The development of wood – based composites testing methodologies for delamination detection must be encouraged as part of the efforts being made to control the performance of low cost building materials.

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