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Finite element analyses in wood research: a bibliography

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Abstract This paper gives a bibliographical review of the finite element methods (FEMs) applied in the analysis of wood. The added bibliography at the end of this article contains 300 references to papers and conference proceedings on the subject that were published between 1995 and 2004. The following topics are included: Wood as a construction material—material and mechanical properties; wood joining and fastening; fracture mechanics problems; drying process, thermal properties; other topics. Wood products and structures—lumber; glulam, panels, wood composites; trusses and frames; floors, roofs; bridges; other products/structures.

Introduction

Wood can be characterized as a natural, cellular, polymer-based, hygrothermal viscoelastic material. As a construction material, it has been used very early next to stone, owing to its good material and mechanical properties. To name some of them: wood is strong in relation to its weight; good heat and electrical insulator; easily machinable; it can be fabricated to a variety of shapes and sizes; and not the least important- economically available. Wood is a renewable and biodegradable resource. Its main drawbacks are: wood is an anisotropic material with an array of defects in the form of irregular grains and knots; it is subject to decay if not kept dry, and it is flammable.

In the last four decades, the finite element method, FEM, has become the prevalent technique used for analyzing physical phenomena in the field of structural, solid and fluid mechanics as well as for the solution of field problems.

This paper gives a review of the published papers dealing with finite element methods applied to wood. For a more efficient information retrieval, the list of

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references of papers published between 1995 and 2004 is classified into the following topics:

- Wood as a construction material
  - Material and mechanical properties
  - Wood joining and fastening
  - Fracture mechanics problems
  - Drying process, thermal properties
  - Other topics
- Wood products and structures
  - Lumber
  - Glulam, panels, wood composites
  - Trusses and frames
  - Floors, roofs
  - Bridges
  - Other products/structures

This bibliography is organized in two parts. In the first, each topic is considered and current trends in the application of finite element techniques are mentioned, usually in form of keywords. The second part lists papers published in the open literature for the period 1995–2004 on subjects presented above. References have been retrieved from the author's database, MAKEBASE. Also the COMPENDEX database has been checked. Hopefully,

This bibliography will save time for readers looking for information on wood and wood products/structures where finite elements are applied in the analysis/simulation process. Readers interested in the finite element literature in general are referred to the author's Internet Finite Element Books Bibliography (http://www.solid.ikp.liu.se/fe/index.html) where approximately 500 book titles are listed complete with bibliographical data, abstracts and book-contents.

Wood as a construction material

In this section, wood as a construction material is considered in the following subsections: material and mechanical properties; wood joining and fastening; fracture mechanics problems; drying process and thermal properties; and other topics.

Material and mechanical properties

Wood is an anisotropic material but under the appropriate set of conditions, is usually considered to be orthotropic (in numerical analysis). Wood is an orthotropic material with an array of defects in the form of irregular grains and knots. When it is used as a structural material, the accurate knowledge of its mechanical properties is necessary. Wood as an orthotropic material has three planes of symmetry defined by longitudinal direction along fibers, radial direction parallel to the rays, and tangential direction to the growth rings. The complex stress-strain relationships referred to three planes of symmetry characterize the mechanical properties. Their knowledge is necessary for the design of wood structures or their members.

Wood is a material with a microstructure reflected on the macroscale in its grain. Cell walls are layered and contain three organic components: cellulose, hemicellulose and natures adhesive, lignin. The lay-up of cellulose fibers in the wall is complex but important because it accounts for the part of the great anisotropy of wood.

Mechanical properties of wood are complex because they exhibit variable behavior with time, temperature, moisture or loading rate. The linear relationship is observed in longitudinal and transverse tension; in compression and shear, the stress-strain relationship is nonlinear. This section deals with constitutive models of wood materials that are implemented in linear/nonlinear finite element procedures.

Studies of wood from a micro to a macrolevel are necessary for a more precise definition and understanding of material and mechanical behavior of wood. At the microlevel, the fiber shape, cell wall thickness, etc. are included in modelling. Their continuum properties can be derived by use of a homogenization procedure and the finite element method. The stiffness, shrinkage and, finally, the constitutive model is determined in various levels and then used in numerical simulations.

Main topics include: 2D and 3D constitutive modelling; coupled material modelling; micro- and macromechanical studies; linear and nonlinear mechanical properties; identification of material and mechanical parameters; influence of knots; influence of geometrical distribution of cell-walls; effect of polar anisotropy; strain localization problems; evaluation of nonhomogeneities; estimation of shear moduli; internal stresses of a growing tree.

Materials under consideration: wood, timber; cellular solids, ash wood; sugi lamina; pinus radiata; pinus pinaster ait.

Wood joining and fastening

Connections in wood structures are made with a variety of fasteners and other materials. To name some of them: nails, bolts, screws, staples, shear plate connectors, nail plates, metal connection hardware, split ring connectors. Wood members can be connected to each other or to another material, i.e., metal.

Wood components are usually designed for uniaxial loading in grain direction. Unfortunately, all types of joining locally induce multiaxial state of stress. Wood joints can often be the weakest point in the structure resulting in a reduction of its global strength. The knowledge of mechanical properties of wood joints is therefore required. The finite element method is a suitable tool to study the mechanical performance of reinforced and non-reinforced wood joints affected by the various parameters. The singularity of joints is due to a combination of different materials and also due to the anisotropy of wood.

The main source of ductility in wood structures is in the mechanically fastened joints, especially those with dowel-type fasteners such as nails and bolts. Nonlinear finite element method has been used to predict load-slip response of nailed joints under a monotonic as well as reversed cyclic loads. Nailed joint properties such as strength degradation, energy absorption, ductility, etc. have been determined.

In wood bolted joints, the mechanical behavior is due to relatively low member thickness to bolt-diameter-ratio. It is very complex and studies of material, geometric and loading parameters are necessary. Friction, clearance of bolts, and geometric parameters influence the introduction of high localized stress concentration in the area of contact. Again, the finite element method is an efficient tool for the analysis. References to these studies can be found in the second part of this paper.

Topics include: 2D and 3D finite element analysis of wood joints; analysis of multicontact problems; modelling the interface; influence of geometry on strength; prediction of load carrying capacity; connections under fire exposure.

Type of joint: finger joint; tension-splice joint; dowel-type joint; nailed joint; bolted joint; cross-halved joint; through-tenon joint; glued joint; corner joints; truss joint; double lap joint; rigid and semi-rigid connections; plain and retrofitted connections.

Fracture mechanics problems

In this section, fracture characteristics of wood as a construction material, wood joints, and wood products/structures are handled. The orthotropic behavior of wood means that for using the concepts of fracture mechanics, six planes of crack propagation exist.

Wood is regarded as a brittle material, depending on stress direction, duration of loads and the moisture. Different wood species of softwoods as well as hardwoods due to the orthotropic nature have been studied by finite elements in various crack propagation systems. The maximum load is used to calculate the critical stress intensity factor considering the orthotropic nature of wood and this indicates the resistance against crack initiation. Softwoods and hardwoods are quite different in their microstructures. Studies in softwoods showed the stable crack propagation in contrast to hardwoods where the unstable crack propagation appears followed by crack arresting.

Shear strength is the important parameter for the evaluation of adhesive bonds because it is the most common interfacial stress under service conditions. It is also the evaluation criterion for wood adhesives. Shear test methods can evaluate the shear moduli and shear strength of wood. Different methods and geometries for shear specimens are in existence but they are not yet standardized. Frequently made mechanical tests can be simulated by finite element method.

Fracture mechanics studies of glulam beams with and without holes have been done where stress intensity factors are calculated for different loads by the finite element method. Then crack predictions are given for different combinations of loads forming the base for a design proposal.

Another method to characterize interlaminar fracture is by energy approach, where the strain energy release rate is used as a measure of the fracture resistance. However, fracture of wood and wood structures still need more understanding.

The following topics are listed: 2D and 3D finite element analysis of fracture mechanics problems; large deformation and fracturing process; mode I, II and III loading; tension strength; shear strength prediction; strength in compression; fracture toughness; interlaminar fracture toughness; orthotropic fracture toughness; crack growth; defibration of wood; log-end cracks; crack tendency on surfaces; kink band formation; fracture formation on growing surfaces; mixed mode fracture; estimation of yield and ultimate strength; low cycle fatigue; failure in joints; influence of impregnation on strength; prediction of long-term performance; material testing.

Materials under consideration: wood; timber; lumber; wood composites; wood-wood; softwood; glulam lamellas; various wood species; hybrid materials.

Drying process, thermal properties

Wood is a hygroscopic material. A drying or wetting process simulation involves three fundamental phenomena: heat transfer, the movement of moisture, and mechanical deformation. Swelling and shrinkage creates internal stresses that can be followed by degradation and shape distortion. Wood exhibits orthotropic behavior as well as time-dependent deformations. These deformations are usually split into viscoelastic creep (constant moisture content) and mechano-sorptive creep (varying moisture).

In addition to being overstressed, the wood products can be damaged by decay, fire, insects, etc. To prevent decay, wood has to be kept continuously dry. The process of drying has been simulated by finite element method and a list of papers of constitutive models for wood, considering moisture content effects, can be found in respective part of the bibliography.

Topics listed: finite element simulations of drying process; symmetric and nonsymmetric drying; vacuum drying; high temperature drying; heterogeneous wood drying; wood deformation in drying; stresses and strains in drying; creep problems; mechano-sorptive creep; wood under moisture change; performance of timber in variable climates; thermal fire resistance.

Materials: wood; timber; spruce; oak; pinus radiata; softwoods.

Other topics

Cutting mechanisms of wood where a hybrid cellular/macroscopic finite element method is applied is one of the main topic of this subsection.

Other topics handled: finite element simulation of wood machining; chip formation; cutting force determination; wood cell collapse during cutting; residual stresses after cutting; laser ablation of wood surfaces; modelling of circular saws; saw blade vibrations; using resin to improve the hardness; acoustic properties of wood; wave propagation.

Wood products and structures

There are many wood products available including solid lumber, glued laminated timber, plywood, orientated strand board, etc. Other products such as wood composite I-joists or structural composite lumber can today replace solid lumber.

Wood structures have to resist vertical loads (gravity loads) and lateral forces (earthquake, wind). There are also other factors to be considered such as dead load, floor moving load, roof snow load, etc. By means of finite element methods, actual stresses in structural members/structures are evaluated and checked against the allowable stresses.

Wood as a construction material is used first of all in civil engineering structures/infrastructures subjected to static or dynamic loads. Wood under static or quasi-static loads is used for example in trusses, buildings, bridges;

wood under impact loading is used in roadside safety structures. Other applications: furniture, musical instruments, sport equipment, etc.

This section contains the following topics: lumber; glulam, panels and wood composites; trusses and frames; floors and roofs; bridges; and other products.

Lumber

Sawn lumber of rectangular cross section is available from a variety of species, and a variety of stress grades is available for each species group.

Topics listed: failure modelling of sawn lumber; material testing of lumber; torsion rigidity and lateral stability; reduction in tensile strength.

Glulam, panels, wood composites

Structural glued-laminated timber (glulam) is formed by gluing together small pieces of wood to form requested size of structural members. It is a versatile material that can be produced in many sizes and shapes. Glulam reduces the effect of imperfections in individual pieces and allows that large members can be produced economically. The problems are the joints, where failure may occur due to splitting parallel to the timber grain.

Structural composite lumber is a reconstituted product and according to its manufacturing can be either laminated veneer lumber or parallel strand lumber. The first named lumber is formed by gluing together thin sheets of wood, the second one is formed by gluing together thin narrow pieces. Structural-use panels are wood panels with directional properties, known as plywood or as oriented strand board.

Fiber reinforced composites are often used to reinforce wood, specifically glulam wood beams, because of their favorable properties such as light weight, high stiffness and strength, and corrosion resistance. This arrangement decreases the volume of wood and increases the stiffness and strength.

Type of hybrid materials or wood structures listed: layered timber beams; glulam beams; glulam beams with holes; flexural reinforcement of beams; arch-shaped beams; OSB webbed timber I-beams; panels; stiffened panels; fiberboard; strandboard; plywood; carbon fiber reinforced plywood; particleboard; chipboard; corrugated fiberboard; boards; OSB panels; glulam members; wood composites; laminated composite structures; cross-ply laminates; adaptive wood composites; strand-based wood composites; layered wood composites; composite cored trapezoidal sections; timber/concrete composites.

Trusses and frames

Another group of wood products are composite structural products such as prefabricated wood trusses, I-joists or wall panels. Most wood frames combines horizontal diaphragms and shear walls.

Finite element method has been used for 2D and 3D nonlinear studies of wood frame structures under static and dynamic loadings. These studies make it possible to better understand some important issues such as load sharing among structural components and load paths within the entire system. Also various connection configurations have been simulated.

Not only the individual components, but also the static and dynamic finite element studies of light-frame wood buildings have been done. These buildings consist of an assembly of vertical, horizontal and diagonal diaphragms connected along their edges. The low weight-high stiffness ratio, the flexibility and the redundancy are main reasons for the wood usage in the construction of buildings.

Wood structures/members listed: wood trusses; timber girder trusses; composite space trusses; wood truss joints; compression webs in wood trusses; glulam truss structures; truss webs and chords; wood frames; light-frame timber structures; light wood-framed buildings; timber buildings; wood diaphragms; wood-framed diaphragms; wooden domes; timber lattice domes; reticulated timber domes; wood-framed shear walls; shear walls; shear walls with openings.

Floors, roofs

Finite element method has been used for predicting static and dynamic response of wood-based floor structures with and without lateral reinforcements. In the analysis also other structural features can be considered such as different connector elements, gaps perpendicular to joists in the subfloor, additional objects on floor and flexible supports.

The finite element method examines the load-sharing properties of wood-joist floor systems subjected to a concentrated load. Then moment and deflection design equations are developed to account for load sharing. Factors contributing to load sharing are partial composite action, variability of material properties.

Finite element parametric studies have been done to determine shear and flexural deflection components of the maximum deflection of joisted oriented strand board (OSB) floor panels with edge support, subjected to concentrated load.

Wood systems considered: wood-based floors; wood-based floors with lateral reinforcements; floor decking; OSB floor decking; joisted decking; wood-joist floor systems; wood-concrete floor/deck systems; hardwood athletic flooring systems; timber roofs; wood-frame roofs; strengthened frame roofs.

Bridges

Development and construction of wood bridges requires the static, but first of all the dynamic analysis, where the bridge is subjected to traffic and wind loadings. Nonlinear and damping properties of these structures can initiate significant dynamic displacements resulting in instabilities. The finite element technique is an efficient method to provide these computations.

Type of bridges listed: timber bridges; arch bridges; T-system timber bridges; slender wood bridges; timber-concrete bridges.

Other products/structures

The following wood products/structures are handled: wood pole structures; historic timber structures; wooden bell-towers; wood-based stair stringers; wooden spiral staircases; musical instruments; furniture; box-type furniture;

furniture joints; corrugated boxes; baseball bats; wood railroad crosstie; composite-reinforced wood railroad crosstie; guardrails timber posts; W-beam guardrails; bamboo scaffolds.

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Acknowledgements The bibliography presented is by no means complete but it gives a comprehensive representation of different finite element applications on the subjects. The author wishes to apologize for the unintentional exclusion of missing references and would appreciate receiving comments and pointers to other relevant literature for a future update. This bibliography can assist researchers interested in the subjects described but not having the access to large databases or not willing spend their time on their own, for time-consuming information retrieval.