DEPARTMENT OF CIVIL ENGINEERING
TECHNICAL UNIVERSITY OF DENMARK

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STAFF related to the topic reliability of timber structures:

Senior scientists:

Lars Damkilde
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An average turover of six M.Sc. students and one 1 Ph.D. student per year in the area of wood science and engineering

The department has a total staff of 86 senior scientists, 33 technicians and 18 administrative personnel

More information to be found at:
http://www.dtu.dk/index_e.htm

NOTEWORTHY EQUIPMENT:
Workshop for woodworking including finger joint cutting

15 testing machines covering the range from 5 kN to 10 MN among which are 6 hydraulic fatique testing machines

10 pneumatic fatigue testing machines

200 large size bending creep rigs

144 small size bending creep rigs (panel products)

20 compression creep test rigs

16x30 m^2 strong floor

4 large sized conditioning rooms

200 m^2 of test rooms providing varying climate facilities

X-ray equipment for combined density and moisture measurements

5 conditioning chambers for precision measurements of sorption properties

Equipment for suction measurements

Microcalorimeter and 0,5m^3 autoclave

Digital image processing system

KEY WORDS:

Timber engineering, creep, duration of load, fatigue, fracture mechanics, micromechanics material modelling, reliability, constitutive modelling, adhesive joints, adhesives, connections, composite structures, finite elements, mechanosorptive behaviour, wood-moisture relations, diffusion, moisture transport, non-destructive testing, wood anatomy, timber drying, hygrothermal treatment

PROJECTS RELATED TO RELIABILITY OF TIMBER STRUCTURES:

FATIGUE DAMAGE IN WOOD

The aim is to investigate the interaction between number of cycles and time under load in the formation of fatigue failures.
The hypothesis is that fatigue damage in wood can not alone be described by number of cycles to failure, the traditional Wöhler approach, as the duration of load influence the fatigue strength even at stress levels under what is considered the DOL-threshold. Interaction between number of cycles and DOL has been shown for high stress values in compression parallel to the grain. The main focus of the experimental work is to investigate the interaction between number of cycles and DOL in tension perpendicular to the grain at stress levels round 60 % of the short term strength. Interaction is not traceable at 12 % MC but weak interaction appears at 18 % MC.

References:
Clorius, C. O., Pedersen, M. U., Hoffmeyer, P., Damkilde, L., 2000: Compressive Fatigue in Wood. Accepted for publication in Wood Science and Technology

Clorius, C. O., Pedersen, M. U., Hoffmeyer, P., Damkilde, L, 1999: Fatigue in Tension Perpendicular to the Grain. Proceedings of The Pacific Timber Engineering Conference, Rotorua, New Zealand, Ed. B. Walford, Vol. 3, pp. 406—413.

Clorius, C. O., Pedersen, M. U., Hoffmeyer, P., Damkilde, L., 1999: Wooden Bridges -- Phase 2, Subproject 2.3 Fatigue. Nordic Timber Council AB, Stockholm.

STRENGTH CRITERIA FOR TIMBER CONNECTIONS

The aim is to investigate the validity of plasticity based design in connections influenced by tension perpendicular to the grain.

The hypothesis is that the empirically based end distance and spacing requirements are insufficient when dowel type connections are loaded with a significant component perpendicular to the grain. In the Eurocode the strength of dowel type connectors is determined according to the theory of plasticity. Experimentally the plasticity theory is confirmed for loading in the grain direction. However, when the loading is in the transverse direction splitting supervenes plastic failure, i.e. the brittle global capacity of the connection is exceeded before the plastic capacity of the embedment perpendicular to the grain is reached.

References
Pedersen, M. U., Clorius, C. O., Damkilde, L., Hoffmeyer, P., 1999: Strength of Glued-In Bolts after Full-Scale Loading. ASCE, Journal of Performance of Constructed Facilities. Vol 13-3, pp.107-113.

Pedersen, M. U., Clorius, C. O., Damkilde, L., Hoffmeyer, P., Traberg, S., 1999: Size Effect in Tension Perpendicular to the Grain. Proceedings of The Pacific Timber Engineering Conference, Rotorua, New Zealand, Ed. B. Walford, vol. 1, pp. 207-214.

Pedersen, M. U., Clorius, C. O., Damkilde, L., Hoffmeyer, P., Eskildsen, L., 1999: Dowel Type Connections with Slotted-in Steel Plates. 32th. CIB/W18 meeting Graz, Austria. CIB-W18/32-7-8.

LAMINATIONS FOR GLUED LAMINATED TIMBER – ESTABLISHMENT OF STRENGTH CLASSES FOR VISUAL STRENGTH GRADES AND MACHINE SETTINGS FOR GLULAM LAMINATIONS OF NORDIC ORIGIN

The aim of the project is to establish the basis for the assignment of characteristic strength values to glulam lamellas. It is the aim to also establish a mutual data base which will in the future be available to researchers from Scandinavian wood research institutions.

Design of glulam according to the European timber code Eurocode 5 is based on the standard document prEN1194 , according to which glulam beam strength is to be established either by full scale testing or by calculation. The calculation must be based on a knowledge of lamination tensile strength. This knowledge may be obtained either by adopting a general rule that the characteristic tensile strength is sixty percent of the characteristic bending strength, or by performing tensile tests on an adequate number of laminations representative of the whole population. The project establishes an adequate experimental background for the assignment of strength classes for glulam made of visually strength graded laminations from Nordic

sawmills. The investigation includes more than 1800 boards (laminations) of Norway spruce (Picea abies) sampled from eight different regions in Scandinavia, two in Norway, two in Finland and four in Sweden. About twenty percent of the sample is tested in bending and the rest in tension. The investigation includes laminations of different depth for the assessment of size effect. The proper glulam classes are asssigned to laminations of the two major visual strength grades currently used in the Scandinavian countries

References:
Johansson, C.-J., Boström, L., Holmqvist, C., Hoffmeyer, P., Solli, K.H. 1998: Laminations for glued laminated timber – establishment of strength classes for visual strength grades and machine settings for glulam laminations of Nordic origin. SP Swedish National Tesing and Research Institute, SP Report 1998:38

Hoffmeyer, P., Bräuner, L., Boström, L., Solli, K.-H., 1999: Tensile strength of glulam laminations of Nordic spruce. Proceedings of PTEC '99, Forest Research Bulletin No. 212, Rotorua New Zealand

RELIABILITY OF TIMBER STRUCTURES
The aim of the project is to establish the necessary theoretical and experimental background for the reliability analysis of timber structures

The project was launched in 2000. It is a cooperative project between Aalborg University, Lund University (Sweden), SP (Sweden), Danish Building Research Institute and BKM/DTU. The department has the responsibility for two sub-projects. One deals with the mathematical characterisation of timber strength distribution with particular reference to the lower tail. The other deals with the modelling of system effects and load sharing in structures such as stressed skin elements and roof trusses.

COMPRESSION STRENGTH PERPENDICULAR TO GRAIN OF STRUCTURAL TIMBER AND GLULAM
The aim of the project is to study the compression perpendular to grain properties with a view to the effect of the support area.

The project provides experimental results based on EN 1193 that may assist in the correct assignment of strength values in compression perpendicular to grain. The dominant failure mode of glulam specimens is shown to be fundamentally different from that of structural timber specimens. Glulam specimens often show tension perpendicular to grain failure before the compression strength value is reached. Such failure mode is not seen for structural timber. Nonetheless, the test results show that the levels of characteristic compression strength perpendicular to grain are of the same order for structural timber and glulam. The study includes a numerical analysis to prove the significant role of tension perpendicular to grain stresses in the failure mode of the glulam specimens. The project includes a study of the effect of support area on the strength across the grain

References
Damkilde, L., Hoffmeyer, P., Pedersen, T.N. 1998: Compression strength perpendicular to grain of structural timber and glulam. Proceedings of CIB/W18 meeting, Finland

Hoffmeyer, P., Damkilde, L., Pedersen, T.N. 2000: Structural timber and glulam in compression perpendicular to grain. Holz als Roh- und Werkstoff., 58(2)

MECHANICAL PROPERTIES OF SITKA SPRUCE
The primary objective of this project is to establish the experimental basis for the assignment of Danish grown Sitka spruce to the European strength class system

Sufficient quantities of representative samples of Sitka spruce specimens are investigated in order to establish the characteristic strength values necessary for entering into the European strength class system (EN 338). All the material tested is subjected to visual grading according to INSTA 142 and the ECE rules. In addition, three different grading machines are included. In addition to the establishment of strength and stiffnes values the relations between the non-destructive parameters and the mechanical properties are studied. The variance between sawmills is quantified. The results have formed the basis for the inclusion (2000) of Danish sitka spruce in EN 1912.

References:
Bräuner, L., Hoffmeyer, P., Poulsson, L. 2000: Mechanical properties of *Picea sitchensis.* Scand. J. For. Res. (accepted for publication)

MODELLING THE EFFECTS OF MOISTURE AND LOAD HISTORY ON THE MECHANICAL PROPERTIES OF WOOD

The aim of the proposed project is to establish a model to predict the mechanosorptive effect on creep and time to failure for timber

The project is launched in 2000 and is aimed at modelling mechanosorptive effects. The material model will describe the creep and duration of load effects as a function of the moisture content and moisture gradients. For completeness the model will also include temperature effects even though this effect primarily is present in the industrial drying process of green timber. The model is formulated in a Finite Element context which enables simulation of complicated configurations. The basis for this model has been established in an earlier project on drying of timber. The common numerical model secures that all of the results in different sub-projects can be combined at a later stage and also secures the possibility of a continued development of a model for timber. The advantage of a numerical model based on Finite Elements is the ability to treat arbitrary geometries, loadings etc. This fact is very important for timber as a natural grown material with a variety of anomalies such as fibre inclination, knots, reaction wood etc. The large spatial variations also implies that the numerical model has to be full 3-dimensional.

DURATION OF LOAD OF DIFFERENT SIZED TIMBER BEAMS

The aim of the project is to study the combined influence of moisture variations and size on the duration of load properties for glued laminated timber

The hypothesis is that the mechanosorptive effect, which is known to significantly shorten time to failure of timber, is less important for large sized beams. The reason is that moisture variations are simply less for large dimensions than for small dimensions. An additional purpose of the project is the assessment of the long-term strength of finger joints The strength of a glulam beam is to a large extend determined by the strength of the finger joints of the glulam lamellas. The duration of load behaviour of a glulam beam is therefore dependent of the static and dynamic fatigue of the finger joints. The knowledge of the static fatigue of finger joints is scarce, and the information on dynamic fatigue behaviour is even more limited. It is the purpose of the project to investigate whether finger jointed timber exhibits duration of load behaviour significantly different from that of non-jointed timbert of the duration of load factor for large sized glulam beams. The project is a cooperative study between LTH, Sweden, LRBB, France, VTT, Finland and DTU/BKM.

References:

Gustafsson, P.J., Hoffmeyer, P., Valentin, G. 1998: DOL behaviour of end-notched beams. Holz als Roh- und Werkstoff, 56: 307-317

Hanhijärvi, A., Galimard, P., Hoffmeyer, P. 1998: Duration of load behaviour of different sized straight beams subjected to bending in variable climate. Holz als Roh- und Werkstoff, 56: 285-293

DRYING OF WOOD – WITH SPECIAL REFERENCE TO SITKA SPRUCE

The aim of the project is to contribute to the modelling of moisure movements in timber

A Finite Element model is produced which models the movement of water in wood as a function of the environment. A new x-ray equipment is produced which can simultaneously measure dry density and moisture in a scanning pattern thus enabling the non-destructive assessment of moisture movements in wood. Sitka spruce is used as model wood. Twist is monitored for a large number of boards. A limited number of these are then subjected to a detailed study of the variation of properties across the cross section. The variation is entered into the FEM model and a verification and calibration is carried out.

ANALYSIS OF LIFETIME AND RESIDUAL STRENGTH OF WOOD. Lauge Fuglsang Nielsen.

Working paper for the CTBA seminar October 2-3 1997 on Reliability based designof timber structures), Building Materials Laboratory, Technical University of Denmark

The paper is thought of as a working paper for the CTBA-seminar on Thematic network in the field for reliability based design of timber structures, Topic: Numerical methods for structural analysis. It is preliminary and quite informal in its structure. The intention is to present some wood technological problems which can be solved with respect to lifetime and residual strength by the so-called DVM-theory (Damaged Viscoelastic Material). The outlines of the paper is straight on: Expressions are presented by which the analysis is made. Then some examples are considered with solutions presented graphically.

The examples are subdivided in two groups. The first group is considered as an average of wood. Another group is considered respecting that each piece of wood is an individual.
Constant loads and variable loads are considered. The latter are assumed to have "seasonal frequencies" with periods greater than 1-2 months. It is also assumed in this paper that loads do not change sign. These assumptions are introduced for simplicity only. The DVM-theory has been generalized in (x,xx) to apply in general for any frequency of load variations with arbitrary average. Two examples are presented just to illustrate the capability of the DVM-theory also to confider such problems.
Some basics of the DVM-theory are presented in sections at the end of the paper. Finally, most often time to start of damage propagation (t_S) is ignored in this paper because it is very often negligible relative to total lifetime (t_{CAT}).

LIFETIME OF WOOD AS RELATED TO STRENGTH DISTRIBUTION IN "RELIABILITY-BASED DESIGN OF ENGINEERED WOOD STRUCTURES". Lauge Fuglsang Nielsen.
(ed. J.Bodig), Kluwer Academic Publishers, Dortrecht, The Netherlands, 1992.

Abstract: Lifetime of wood is related to load level as well as wood quality. The former statement is a matter of course. The latter statement has been justified in recent years both theoretically and experimentally. It is shown in the paper that lifetime distribution is itself a quality dependent quantity. An algorithm is developed predicting lifetime distribution directly from strength distribution. Structural analysis must accept distributions of strength and lifetime of wood to be correlated quantities. A discussion is made on how to extract a maximum of relevant lifetime information from experimental data - and it is finally pointed out that the results obtained in the paper are valid also when a number of other building materials are considered.
Introduction: Any realistic reliability study of structures needs information on how reliable are the building materials being used. A reliability analysis of a wood structure, for example, cannot be made without knowing about strength and lifetime distributions of the wood considered as structural material. Normally, purely empirical distributions are chosen for each event without any guaranty that this procedure will not introduce inconsistency which may influence in some un-known way the results of a reliability analysis.
These considerations indicate the topic of the present paper. It is demonstrated that the two distributions considered are correlated, meaning that lifetime distribution can be predicted from strength distribution. An algorithm is developed for this purpose - and a discussion is made on how to extract a maximum of lifetime information from experimental data.

LIFETIME AND RESIDUAL STRENGTH OF WOOD – SUBJECTED TO STATIC AND VARIABLE LOAD. Lauge Fuglsang Nielsen.
Dept. Struct. Eng. and Materials, Tech. Univ. of Denmark, Tech. Rep. R6(1996).

Abstract: The DVM-theory (Damaged Viscoelastic Material) previously developed by the author to predict lifetime of wood subjected to static loads is further developed in this paper such that harmonic load variations can also be considered. Lifetime (real time or number of cycles) is predicted as a function of load amplitude, load average, fractional time under maximum load, and load frequency. The analysis includes prediction of residual strength during the process of load cycling. It is concluded that number of cycles to failure is a poor design criterion. A simple time criterion is much better. The theory is successfully compared with data from experiments representing different wood products. Master graphs are developed which can be used in fatigue design of wood products in general. These graphs are valid for any creep behavior (relaxation, moisture content) and materials quality (grading, strength level).
It is demonstrated how the theory developed can be generalized also to consider some non-harmonic load variations. An algorithm is presented for this purpose which might be suggested as a qualified alternative to the Palmgren-Miner's method normally used in fatigue analysis of materials under arbitrary load variations. The Palmgren-Miner's method has the disadvantage of not considering creep which may cause considerably overestimated time to failure, especially at low frequencies. Finally it is discussed how the theory can be generalized also to consider other materials such as concrete and other aging viscoelastic materials.
Keywords: Fatigue, Prediction, Lifetime, Residual strength, Variable load, Static load, Viscoelastic materials, Wood, Concrete.

TIME AND RESIDUAL STRENGTH OF WOOD – SUBJECTED TO STATIC AND VARIABLE LOAD. PART I: INTRODUCTION AND ANALYSIS.

Holz als Roh- und Werkstoff , 58(2000). 81-90

Abstract: The DVM-theory (Damaged Viscoelastic Material) previously developed by the author to predict lifetime of wood subjected to static loads is further developed in this paper such that harmonic load variations can also be considered. Lifetime (real time or number of cycles) is predicted as a function of maximum and minimum loads, fractional time under maximum load, and load frequency. The analysis includes prediction of residual strength during the process of load cycling. The paper is divided in two parts.

In Part I (this one) an introduction to the full paper is presented together with a brief discussion of the DVM-model and its ingredients: Viscoelasticity, elastic-viscoelastic analogy, Dugdale crack model (including crack closure). Finally, viscoelastic solutions are developed for the lifetime problems considered. A list of symbols is presented at the very end of the paper.

In a subsequent Part II of the paper, justifications, examples, and applications of the lifetime theory developed are presented together with easy expressions and graphs for design purposes. A common conclusion for the two papers is presented. The results of the fatigue analysis developed is briefly discussed with respect to the Palmgren-Miner's method normally used in fatigue analysis of materials. The Palmgren-Miner's method has the disadvantage of not considering creep which may cause considerably overestimated time to failure, especially at low frequencies.

LIFETIME AND RESIDUAL STRENGTH F WOOD – SUBJECTED TO STATIC AND VARIABLE LOAD. PART II:

Holz als Roh- und Werkstoff , 58(2000). 141-152.

Abstract: A fatigue analysis of wood subjected to harmonic load variations has been developed in Part I of this paper. Lifetime (real time or number of cycles) is predicted as a function of maximum and minimum loads, fractional time under maximum load, and load frequency. The analysis includes prediction of residual strength during the process of load cycling.

In this Part II of the paper, examples and applications of the lifetime theory developed are presented together with easy expressions and graphs for design purposes. A common conclusion for the two papers is presented where the results of the fatigue analysis developed is briefly discussed versus results obtained by the Palmgren-Miner's method normally used in fatigue analysis of materials. The Palmgren-Miner's method has the disadvantage of not considering creep which may cause considerably overestimated time to failure, especially at low frequencies.

Danish Urban and Building Research Institute

Short description of the laboratory		
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Main topics	**Example of Activities**	**Number of Scientists**
Building physics	Claddings of wood Protection of wood by design Moisture in timer frame walls	**5**
Damage mechanics	Strength of timber joints Design of timber structures Safety of timber structures	**3**
Sustainability	Life-Cycle Assessment Alternative insulation materials Use of solid timber elements in buildings	**5**
Main equipment: Testing machines, climate rooms, facilities for accelerated aging, moisture house for full scale testing of exterior walls, climate simulator		

Activities related to the field of COST Action E24

Reliability of timber structures (J. Munch-Andersen, B. Dela)

National research project

This project is a cooperation between Technical University of Denmark and University of Aalborg Technical University of Lund (in Sweden), and Danish Urban and Building Research Institute being the project manager. The project is aimed at improving the basis for defining code parameters in Denmark.

Subtasks in the project are:
- Collecting data for improved statistical data for strength distribution (partial coefficients)
- Collecting data for improved basis for determining reduction factor for load duration
- Collecting data for describing longitudinal strength variations of structural timber
- Investigating system effects by use of models and finite element computations
- Determination of characteristic values and variations of prefabricated rafters and elements

The project is running over a 2-year period and is to finish by the end of 2001.

Nordic Wood project

This project is a cooperation between research institutes from 4 Nordic countries: Finland, Norway, Sweden and Denmark. The scope of the project is similar to that of the national project in Denmark. The project is running over a 2-year period and is to finish in the beginning of 2002.

Design properties of Danish low density softwood (E. Brandt)

The project deals with the use of Danish low-density fast growing softwood as structural timber. Recently, the Danish timber code allowed this type of structural timber having a characteristic bending strength of 14 MPa. A number of constructions have been investigated for the effects on design when using a less strong type of structural timber. The investigations have been theoretical mainly, but tests on connections have been performed as well. The results show that low strength timber can be used in a number of structures with only slight increasing use of material. This is due to the fact that strength is only one of

many design criteria. Other effects may be size due to thickness of insulation or other non-structural purposes.

Mechanical properties of self-cutting screws in wood (K.F. Hansen)
A research program on mechanical properties of self-cutting screws in wood has been made to improve the basis of design of screwed connections in wood. The wood material used in the project is Danish softwood with densities in the range of 350-550 kg/m^3. Tests as well as simple calculation models are used in the project. Tests carried out are:

– Embedding strength
– Withdrawal strength
– Pull-through strength
– Bending capacity of individual screws
– Shear strength of screwed wood-wood connections
– Shear strength of screwed wood-steel connections

The calculation models take dowel action and friction into account and shows excellent agreement with test results.

Aalborg University, Denmark
Department of Building Technology and Structural Engineering

The specialist fields of the Department are centered on disciplines that form the engineering and scientific basis for the development of buildings, comprising load-bearing structures and building services as well as bridge structures and other civil engineering structures.

Teaching
The teaching activities of the Department are primarily related to the BSc programmes in Building Technology and Civil Engineering and the MSc programmes in Structural Engineering and Indoor Environmental Technology. Recently, teaching activities in relation to a new M.Sc. programme on Architecture and Design and a new international Master Education on Indoor Environmental Engineering have been taken up. The latter requires teaching in English. Furthermore, the Department contributes to PhD programmes for all the subject areas, which are covered by the Department.

Research
The research of the Department is conducted within the fields of design methods in building technology, IT in civil engineering, structural reliability, structural dynamics, structural fatigue, fracture mechanics, design and concrete technology. In the field of indoor environmental engineering, research is performed on air distribution and contaminant distribution in rooms, dynamic temperature conditions in rooms and hybrid ventilation. At the Department there are six laboratories: The Structural Research Laboratory, the Indoor Environmental Engineering Laboratory, the Concrete Technology Laboratory, the Fire Laboratory, the Acoustics Laboratory and the IT Laboratory. The Department undertakes contractual research projects for governmental institutions as well as private firms. These projects comprise theoretical research as well as site measurements and experimental tests in the laboratories.

Projects – with relation to reliability of structures

- Stochastic and Computational Models for Destructive Mechanisms.
  For structural systems it is often of large interest to have a rational tool to assess the reliability taken into account the actual condition of the structures. In this project stochastic models for destructive mechanisms are considered, especially ingress of chlorides in concrete and corrosion of reinforcement. Stochastic finite element methods are used to estimate the reliability. Further the application of these models in reliability-based optimal inspection and maintenance is part of the project.
- Reliability Assessment of Structures with Stochastic Material Properties using Stochastic Finite Element Methods.
  The project considers stochastic modeling of material properties for in structural systems where the material properties vary in space. Both material and geometrical non-linearities are considered. On the basis of the stochastic modeling compuational tools are developed and the reliability is estimated using stochastic finite element methods.
- Probabilistisk Design Tools for Vertical Breakwaters
  Significant failure modes are identified for vertical breakwaters. These include geotechnical, hydraulic and structural failure modes. Limit state equations and stochastic models for the wave load (pulsating and impulse loads) and other uncertain parameters are formulated. Methods to estimate the total reliability are investigated and the reliability level of typical vertical breakwaters are derived. Finally the derivation of consistent partial safety factors are considered.
- Requalification of Offshore Structures
  The objective of the project is to develop new, practical applicable methods which on a rational probabilistic and decision theoretical basis can be used in re-assessment of offshore platforms and pipelines. An economic decision model is developed where relevant economic aspects in the expected remaining lifetime of a structure are included. A new stochastic model directional significant wave heights is developed. Further the concept of generic reliability-based optimal inspection planning is developed and exemplified.
- Reliability of Timber Structures
  Statistical analysis of basic material properties (bending, compression and tension strength, modulus of elasticity and density) of structural timber is performed on the basis of some very large databases. Mechanical / stochastic models for representative structural systems of timber (timber trussed rafters and roof elements) are developed and the statistical characteristic (coefficient of variation and 5%

quantiles) of these systems are derived. The system effect on the reliability and the influence on the partial safety factor are investigated.

Other projects:

- Reliability Assessment of Offshore Platforms exposed to Wave-in-deck Loading
- Reliability of Systems for Active Control of Vibrations of Structures
- Development of Probabilistic Design Method for Natural Ventilation
- Reliability of Wind Turbine Structures