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Final report for the BFR-project

FINGER-JOINTS AND LAMINATED WOOD

BFR-project no. 19960633

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Preface

This report is the final report for the research project "Finger-joints and Laminated Wood" ("Fingerskarvar och lamellerat trä"), which has been running at the Division of Structural Mechanics, Lund University since 1997. The project has been financially supported by the Swedish Council for Building Research (BFR) (project no. 19960633).

The research performed during these years have, among other things, resulted in a doctoral thesis [14], and this report is a subset of that thesis, containing the results related to finger-joints and laminated wood. The research on wood adhesive joints has led to increased knowledge and new methods in terms of fracture characterisation of wood-adhesive bonds, and this in turn has led to the participation in other research programmes and new applications for the analysis methods. The financial support from BFR, which made all this possible, is gratefully acknowledged.

Lund, December 2000

Per Johan Gustafsson and Erik Serrano

Abstract

This report gives an overview and summary of research on wood-adhesive bonds performed during several years in a number of separate studies. These studies concern the mechanical testing, numerical analysis and constitutive modelling of wood-adhesive bonds in timber engineering. Applications such as finger-joints and glued-laminated timber are considered. The experimental studies include the testing of the fracture characteristics of wood-adhesive bonds. The numerical studies relate to the strength of finger-joints and laminated beams.

In the experimental studies, the complete stress-displacement response of small specimens, particularly their fracture softening behaviour beyond peak stress, was recorded. A major outcome from the experiments is that wood-adhesive bonds can behave in a fracture-softening manner, and that it is possible to record this under stable conditions.

In one of the numerical studies the finite element method was employed to analyse the stress distribution around zones of low stiffness in a laminated beam. A fracture mechanics analysis was also performed of the delamination of a laminated beam. The results show that the often made assumption of a stress redistribution taking place around weak zones is not necessarily true. Another finding is that the delamination of an initially cracked glulam beam tends to be increasingly dominated by mode II failure as the lamination thickness decreases.

In another study, also related to finger-joints and laminated beams, the finger-joint failure in a glulam beam was simulated using a nonlinear fictitious crack model with stochastic properties. The results show the proposed approach to be able to account for such phenomena as the size effect and the laminating effect. Another observation is that finger-joint fracture energy, i.e. the ductility, has a major influence on lamination and beam strength. The influence of bondline defects on the tensile strength of a finger-joint was also investigated. It was demonstrated that even a small defect in the form of a glueline void, can have a relatively strong influence on the tensile strength. It was also demonstrated that the strength of finger-joints is largely influenced by the outermost finger.

Finally, an interface model based on damage mechanics is suggested for the modelling of wood-adhesive interfaces. This model accounts for joint dilatation and post-cracking friction. Also, a homogenisation scheme is presented for combining the proposed model with ordinary plasticity models for the adhesive bulk. This homogenisation procedure is based on assumptions regarding the stress and strain gradients typical of thin bondlines.

Keywords: adhesive, bending strength, constitutive modelling, damage, experiment, finger-joint, finite element method, fracture mechanics, glued-laminated timber, joint, laminated beams, laminating effect, numerical simulation, size effect, stress distribution, tensile strength, test method, wood

Sammanfattning

Trälimfogar är en väsentlig del av modern träkonstruktionsteknik. För att höja förädlingsvärdet hos träråvaran, tillverkas idag flera olika sorters produkter vilka är beroende av limfogar. Exempel på sådana produkter är limträ och fanérträ (LVL).

För att förstå och kunna modellera exempelvis limträbalkars mekaniska beteende, måste man även kunna beskriva limfogarnas inverkan. Även om limfogar ofta utgör en geometriskt liten del av en konstruktion är deras beteende ofta avgörande för hela konstruktionens bärförmåga.

Denna rapport handlar om experimentella och numeriska metoder för att beskriva trälimfogars mekaniska beteende. Speciell vikt har lagts vid limfogarnas brottmekaniska beteende. Med brottmekaniskt beteende menas det som händer i limfogen när limfogens lokala styrka har uppnåtts och en spricka utvecklats. Rapporten utgör en sammanfattning av flera publikationer som beskriver dels experimentella och dels numeriska undersökningar av trälimfogar.

De experimentella metoderna omfattar studier av trälimfogars brottmekaniska beteende. De egenskaper som bestämts är styvhet, styrka, brottenergi samt spännings-förskjutnings kurvors utseende. Vid bestämning av spännings-förskjutningssambanden har särskild vikt lagts vid att registrera den nedåtgående delen efter maxspänning. Undersökningarna visar att trälimfogars beteende karakteriseras av en sådan nedåtgående del och att detta brottmjuknande kan mätas under stabila förhållanden.

De numeriska undersökningarna syftar till att beskriva limfogens inverkan på konstruktionselements mekaniska respons. De konstruktionselement som har behandlats är fingerskarvar och limträbalkar. Resultaten av de numeriska studierna visar att limfogens inverkan kan vara avgörande för dessa konstruktionselements bärförmåga. Det visar sig också att inte bara fogens lokala styrka (hållfasthet) är en viktig parameter. I många fall är limfogens brottenergi och de ingående materialens styvheter de helt avgörande parametrarna.

Contents

Chapter 1

Introduction

1.1 Adhesive Joints in Timber Engineering

Wood-adhesive joints play an important role in modern timber engineering. In order to add value to the raw material, several highly engineered wood-based products have been developed. Often these involve the use of adhesive joints. Typical examples of such *reconstituted* materials are glued-laminated timber (glulam) and laminated veneer lumber (LVL). In each of these, adhesive joints are used both for lengthwise splicing and for interlaminar bonding.

In order to fully understand and model the behaviour of such structural elements as glulam beams, one must also understand the behaviour of their adhesive bondlines. Although adhesive bondlines often represent only a small part of a structural component, they are often crucial parts for the strength and the reliability of the structural component. A typical adhesive bondline in timber engineering has a thickness in the range of 0.1–1 mm, which is several orders of magnitude smaller than the scale of the structural components, one of approximately 0.1–10 m, Figure 1.1.

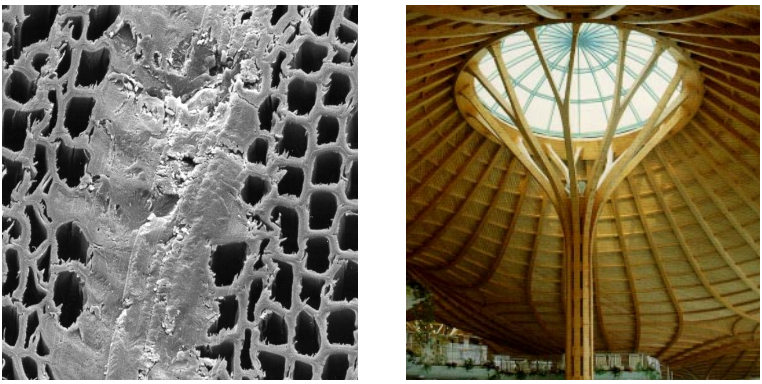

Figure 1.1: Adhesive bonds based on phenol-resorcinol (left) are often used in the production of glued-laminated timber (right).

The work presented concerns experimental and numerical studies of mechanical behaviour on both these scales. The work also concerns new methods for bridging the gap between the two scales, making it possible to incorporate knowledge of the mechanical behaviour of a thin bondline into analysis on the structural-component-size scale.

1.2 Background

1.2.1 Wood As a Building Material

The advantages of using wood as a building material are well known: it has an attractive appearance, is easy to work with, its strength/weight ratio is high, it has comparatively good heat-insulation properties, it retains its strength for a reasonably long period of time if exposed to fire, it is a fully renewable building material and, finally, it is a building material that does not contribute to the green-house effect. There are certain well-known disadvantages, as well, in the use of wood. As a "living" material, its properties vary within a wide range; wood is also a highly anisotropic material, with low strength perpendicular to the grain; finally, wood is known to be sensitive to exposure to moisture.

The large variability in strength, for example, is due to more than simply variations between different trees and stands. Even within a single log, the variability can be extensive. This can be explained by the presence of such anomalies as reaction wood, knots, spiral grain and density variations. Differences in climate during the life of a tree, along with a variety of other factors, likewise influence the variability of the material properties within a log.

Even if one considers wood to be a homogeneous material, it is still a challenging task to measure the basic material properties that are needed for a simple linear elastic stress analysis. Wood is a highly anisotropic material that is often regarded as being orthotropic. The degree of anisotropy is extremely high; typical ratios of Young's moduli and tensile strengths in different directions, are in the order of 1:30–1:50. The strength in tension and in compression also differ (in all directions), and the failure characteristics vary from brittle failure (tension parallel to the grain) to quasi-brittle failure (tension perpendicular to the grain and shear) to ductile failure (compression). Instead of regarding wood and timber as cheap and unsophisticated materials compared with materials that are man-made, we should indeed endeavour to meet the challenge that nature provides and develop further the methods used for testing and analysing wood and wood-based materials so as to discover new applications for wood and timber products.

1.2.2 Engineered Wood-based Materials

To avoid some of the disadvantages of solid wood, several engineered wood-based materials have been developed over the years. Many of these are produced using the same basic approach: cutting solid wood into smaller pieces (sheets, laminations or even fibres) and putting them together again by pressing and gluing them, sometimes at elevated temperatures, as in the case of fibreboards. Such reconstituted materials are more *homogeneous* than solid wood, and their material properties, such as stiffness and strength, do not vary as much as in solid wood. If the raw material is disintegrated into fibres or particles, which are then randomly oriented in the end product, the result is a material that is less orthotropic than solid wood. In such reconstituted materials, the properties of the raw material have been levelled out, the lower variability attained being favourable since it results in higher design values.

1.2.3 Wood-adhesive Bonds

To obtain a reconstituted material that is reliable, it is of utmost importance to have reliable adhesive systems. As far as laminated products such as glulam and LVL are concerned, there are two types of adhesive bonds: those between the different laminations or sheets, and those in the lengthwise splice of continuous laminations. Lengthwise splicing involves the use of scarf joints for LVL and of finger-joints for glulam. Finger-joints are also used in the production of structural timber.

The wood-adhesives most commonly employed in structural applications today are phenol-resorcinol based adhesives (PR), (melamine) urea formaldehyde ((M)UF), polyurethanes (PUR) and epoxies (EPX). Epoxy-based adhesives are reliable and are well suited for structural purposes but are not preferred in some countries for reasons of the working-environment.

1.2.4 Glued-laminated Timber and Finger-joints

For approximately a century, glued-laminated timber or *glulam*, has been used as a material with enhanced performance as compared with solid wood. Glulam is obtained by stacking a number of boards or laminations on top of each other to form a beam cross-section.

In order to obtain laminations of arbitrary length, the boards are finger-jointed prior to being glued together to form the cross-section desired. A commonly used adhesive in Sweden has traditionally been phenol-resorcinol (PR), for finger-jointing as well as for the gluing of laminations. During the last ten years or so, however, the use of melamine-urea-formaldehyde (MUF) adhesive has increased, since this adhesive has the advantage of being transparent, in contrast to PR adhesive, which is dark brown. After the laminations have been glued to form a particular cross-section, the beam is planed to obtain the shape desired.

The advantages of glulam as compared with solid timber are often said to be the following:

- Improved strength and stiffness, mainly because the variability of these parameters is less than in solid wood.
- Freedom in the choice of cross-sections, lengths and curvatures of the beams.
- Possibility to match the lamination qualities within the cross-section in relation to the expected stress levels (strong, high-quality laminations being placed in the outermost zones of the cross-section).
- Improved accuracy of dimensions and stability of shape during exposure to variations in moisture.

1.3 Organisation of Report Contents

This report is an overview and summary of several studies on wood-adhesive bonds. It can be regarded as an extended abstract of the journal articles, theses conference papers and technical reports listed in Appendix A. In the following chapter a brief overview and summary is given, which relates mainly to the theses and journal articles.

Chapter 2

Overview of Present Study

2.1 Aim and Scope

The aim of the researc, is to contribute to the field of timber engineering in terms of experimental methods, rational modelling and numerical methods for the mechanical analysis of wood-adhesive joints. The scope and original features developed to fulfil this aim are as follows:

The paper [17] reports on strength and stiffness analyses of laminated beams in bending. The methods traditionally used for such analyses are addressed. It is demonstrated, by use of simple linear elastic analysis that some of the basic assumptions commonly made in such analyses can be questioned. These assumptions relate to the stress distribution in laminated beams and to load sharing between laminations.

The experimental study reported in [14] concerns testing of the mechanical properties of adhesive bondlines and finger-jointed laminations. The results of this study were later used in [18]. The bondlines are tested in order to record their strain-softening behaviour. Experiments of this type have been reported previously in [19], but the original idea here is that the bondline specimens are cut from finger-joints. This results in the wood fibres being slightly slanted and not being parallel to the bondline. An experimental study of the behaviour of finger-jointed laminations in tension under clamped conditions is also presented. Here, a new evaluation method was used for assessing the normal force and the bending moments that evolve during the testing of the clamped specimen.

The paper [16] reports on a numerical study of the mechanical behaviour of finger-joints. Such studies have been previously reported, but here the response of a complete finger-joint is simulated, instead of using assumptions regarding the boundary conditions of a small part in the interior of a finger-joint. The key issue in this paper is the influence of bondline brittleness and of defects on the strength of a finger-joint.

The paper [18] suggests a new modelling approach to the simulation of finger-joint failure in glulam beams. It involves the use of a stochastic fictitious crack model to characterise a finger-joint. Unlike previous studies of finger-joints, this model makes it possible to study the progressive failure of a finger-joint.

In the thesis [15], finally, a new constitutive model for wood-adhesive bondline interfaces is suggested. This model, based on damage mechanics, incorporates the effects of joint-dilatation and post-cracking friction. A modelling approach which combines the suggested interface model with a traditional elasto-plastic model of the adhesive bulk is also presented.

2.2 Strategy and Methods

The strategy employed can be characterised as a multilevel approach in which the results at a smaller level are used in the subsequent analysis at a higher level. As an example, a constitutive model for wood-adhesive bondline interfaces is suggested in [15]. This model can be used in the analysis of a finger-jointed lamination for example, such as in [16]. Such an analysis results in a prediction regarding the mechanical behaviour of a finger-joint, a behaviour that can be used as an input in the glulam modelling approach adopted in [18].

Another way of describing the strategy employed, is in terms of the methods used on different scales, where performing an experimental study provides the information needed for the theoretical models used to characterise the bondline, for example. These small-scale bondline tests are also subjected to numerical analyses, the material parameters being determined in an iterative manner. Using a set of appropriately calibrated parameters, the constitutive model is employed in numerical analyses of structural-sized joints. These analyses can then be calibrated again and be verified by tests on a larger scale. Having a calibrated model of a structural-sized joint, it is possible to conduct parameter studies of factors which influence joint strength, for example.

A brief review of the methods used in the present study in relation to certain previous work by others is provided below.

2.2.1 Experimental Studies

Over the years there have been a number of experimental studies of the behaviour of *finger-joints*. Examples of this are the work done by Selbo [13], Johansson [8, 9], Radovic and Rohlfing [12], Ehlbeck *et al.* [6] and Colling [5]. The experimental study presented in [14] likewise concerns the behaviour of finger-joints. The test setup used was designed especially to simulate the constraints placed on a lamination when it is contained in a beam. This basic idea has also been employed in other experimental investigations [5]. A single lamination tested in pure tension without clamping, tends to bend because of knots and other anomalies. This is due to the stiffness not being constant over the cross-section of the lamination. If the same lamination was contained in a glulam beam, the rest of the beam would prevent such bending.

In [14], test methods for the determination of fracture mechanical properties are presented. The test methods employed and evaluation of the test results rely on the use of small-size specimens. Using a specimen of small size yields a more uniform stress distribution than using one of larger size, and also allows the strain-softening response to be monitored in a stable way. By a stable test is meant one which includes the complete descending part of the stress vs. deformation curve of the bondline, beyond peak stress. The test must be performed under displacement control in order to record the results beyond peak stress. It is also essential that the complete test setup, including load-cells, grips and the material surrounding the potential fracture area, be stiff. A stiff setup ensures that a stable fracture can take place, since the amount of elastic energy released at unloading corresponds to the amount of energy dissipated within the fracture process zone.

If the setup is not sufficiently stiff, the energy surplus leads to a sudden and unstable failure. The material parameters determined here are strength, stiffness, fracture energy and shape of the stress vs. deformation curve. Fracture mechanical testing of this type has been performed previously on cementitious materials [11], and also on solid wood [4] and wood-adhesive bonds [19].

2.2.2 Constitutive Models and Numerical Analyses

Studies concerning numerical analysis of the mechanical behaviour of finger-joints have been reported by Aicher and co-workers [1, 2, 3], Milner and Yeoh [10] and Wernersson [19]. In [1, 2, 3] linear elastic fracture mechanics theory and plasticity theory were used, in [10] linear elastic stress analyses were performed, and in [19] a model similar to the one used here was developed and applied. However, all the studies deal with only a small part of a finger-joint using boundary conditions simulating the behaviour of a single finger in the interior of an infinitely wide lamination. Instead, in the present study, a complete finger-jointed lamination is analysed.

Several models have been proposed for analysing the behaviour of laminated beams in bending such as those of Foschi and Barrett (1980), of Ehlbeck et al. (1985) and Colling (1990) – the latter two known as the "Karlsruhe model", and of Hernandez *et al.* (1992), Nestic *et al.* (1994), Faye *et al.* (1996) and Renaudin (1997). All these models, except those of Hernandez *et al.* and of Nestic *et al.*, involve a subdivision of the glulam member into elements, frequently standard finite elements. Loading is applied to the beam, the stresses in all the elements being evaluated. This is done at the centroid of the element, each element having the same height as the lamination. The models of Hernandez *et al.* and Nestic *et al.* use transformed section methods (based on beam theory) to calculate the stresses at mid-depth in each lamination, so as to determine the ultimate load-bearing capacity of the beam. In all of these models, the stress at the mid-depth of a lamination is used as a measure of the risk of failure.

The constitutive models employed are of three different types. In [18], a *fictitious crack model* having stochastic properties was used to characterise the behaviour of a finger-joint in a glulam beam. A standard, commercial finite element program was used in *Monte Carlo simulations* to obtain strength statistics for beam bending and for pure tension in a single lamination.

A nonlinear model based on *fracture mechanics* was used for bondline characterisation. This model is a slightly modified version of a model developed by Wernersson [19], implemented in a commercial finite element code as a *crack band model*. The model is believed to be useful for most cases, although it has certain drawbacks. It is formulated as a nonlinear elastic model with strain softening, and, consequently, it will behave unrealisticly if unloading occurs. The model also fails to take proper account of the influence of joint dilatation and frictional forces at compressive normal stresses perpendicular to the bondline. Especially in the case of glued-in threaded rods in which the failure is located in the rod-adhesive interface, the wedging action and the frictional forces can be of importance. The constitutive interface model suggested in [15] includes the features of unloading, joint dilatation and friction. This new model is formulated in terms of *damage mechanics*.

2.3 Results and Discussion

Some of the major results and conclusions of the present work are summarised here. For a more complete review the reader is referred to the individual publications listed in Appendix A.

2.3.1 Experimental Studies

In [14] the main results are the measured material characteristics, such as strength, fracture energy and the shape of the stress vs. displacement curve of the adhesive bonds. Three different adhesives were tested (PR, PVAc and PUR) under three different loading conditions (shear, mixed mode and normal deformation). The adhesives differed distinctively in their behaviour in terms of strength and ductility. For example, estimates of shear strength were of approximately 19 and 9 MPa for the PR and PVAc adhesives, respectively. The corresponding fracture energies were 1250 and 2080 J/m^2, respectively. Another result of the experiments performed on finger-jointed laminations, was that the test setup revealed an apparent lamination factor of approximately 1.10. Thus, if a conventional test method and evaluation method had been used, the tensile strength of the lamination would have been underestimated by approximately 10%.

2.3.2 Constitutive Models and Numerical Analyses

A common hypothesis regarding what contributes to the so-called laminating effect in glulam beams is that weak zones with low stiffness are less exposed to high stresses since the stiffer material surrounding them acts as a "magnet" to stresses [7]. This hypothesis is addressed in [17]. In this paper, it is concluded that these assumptions, for the stress distribution close to weak zones such as knots or finger-joints, are not necessarily true. For example, in that study a stiffness reduction of 25% in a 30 mm wide zone in the outer tension lamination of a glulam beam was introduced. This stiffness reduction lowered the average tensile stress in the lamination by only 3%. Another result of this study concerns the failure modes obtained in laminated beams. It is demonstrated that *if* the outer tension lamination in a laminated beam has failed, the subsequent behaviour *can* be stable, but only for laminations with a thickness of approximately 10 mm or less.

The numerical study of finger-joint strength presented in [16] highlights various interesting details. It is shown that even small defects can have a decisive influence on finger-joint strength. Since even an undamaged finger-joint contains geometrical discontinuities in terms of sharp corners, for example, the marked influence which a small defect can have is somewhat surprising. For example, introducing a glueline void as small as 1 mm in a finger-jointed lamination, was found to reduce the strength by approximately 10%. Another finding is that the outermost finger in a finger-joint has a decisive effect on the strength of that joint. Introducing the above-mentioned small defect in the bondline of the outer finger was found to influence the strength as much as when this same defect was introduced in all the bondlines (22 of them in the present case). This has implications for comparing finger-joint tensile strength with glulam beam bending strength, since in the latter case the finger-jointed lamination is restrained, so that the outermost finger is highly reinforced.

The major finding of the study reported in [18] is that the suggested modelling approach can be useful if properly calibrated to experimental data. The modelling of the finger-joint by use of a fictitious crack model and of stochastic material data provides a more detailed modelling of a finger-joint, thus contributing to a basic understanding of the phenomenon of finger-joint failure in glulam beams.

The constitutive interface model in [15] allows a more realistic modelling of wood-adhesive joints. The model incorporates the effect of damaged-induced dilatation, i.e. the tendency of the joint, when under shear loading, to move perpendicular to the bondline plane. If this movement is constrained, which it is to a greater or lesser degree depending on the stiffness of the surrounding structure, compressive normal stresses will develop. The model presented accounts for this and also adds frictional stress. In [15], a modelling approach which should be useful in the analysis of thin bondlines is outlined. The basic idea is that of using a homogenisation scheme and making use of certain assumptions regarding the stress and strain gradients across the bondline.

2.3.3 Future Work

The author feels that the modelling approach suggested in [18] should be further investigated, since, thus far, no calibration or verification of the model in terms of beam bending test data has been performed. Another interesting development of the modelling approach proposed would be to employ stochastic modelling for the bondlines between the laminations as well. In principle, it would also be possible to use the stochastic fictitious crack model approach to model wood failure.

The finger-joint modelling presented in [16] concerned a finger-jointed lamination in tension. A further development of this modelling could be to include a full three-dimensional approach. This would make it possible to simulate the flatwise bending tests used in finger-joint production control. It would also make it possible to simulate the behaviour of a complete finger-joint in a beam which is normally exposed to a combination of tension and bending.

The constitutive model outlined for the bondline interface has not been implemented in any finite element code. Doing so should be straightforward. However, the homogenisation method for thin bondlines suggested in [15] is probably less easy to implement.

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Appendix A

Lists of Publications

Below is a complete listing of publications related to the current BFR research project for the time period 1997 – 2000.

A.1 Journal Articles

1. E. Serrano and P. J. Gustafsson. *Influence of bondline brittleness and defects on the strength of timber finger-joints.* International Journal of Adhesion and Adhesives. 19(1) pp. 9–17. 1999

2. E. Serrano and H. J. Larsen. *Numerical investigations of the laminating effect in laminated beams.* Journal of Structural Engineering. ASCE, 125(7) pp. 740–745. 1999.

3. E. Serrano. P. J. Gustafsson and H. J. Larsen. *Modeling of Finger-joint Failure in Glued-laminated Timber Beams.* Submitted for publication in Journal of Structural Engineering. ASCE. 2000.

A.2 Theses

1. E. Serrano. *Finger-joints for laminated beams. Experimental and numerical studies of mechanical behaviour.* Report TVSM–3021. Lund Institute of Technology, Division of Structural Mechanics. Lund, Sweden, 1997. Licentiate thesis.

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A.3 Conference Papers

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2. E. Serrano, H. J. Larsen and P. J. Gustafsson. *Influence of defects on the strength of finger-joints.* Proc. of the 5^{th} World Conference on Timber Engineering, vol. 1, pp. 854–855. August 17–20, Montreux, Switzerland, 1998.

3. P. J. Gustafsson and E. Serrano. *Glued truss joints analysed by fracture mechanics.* Proc. of the 5^{th} World Conference on Timber Engineering, vol. 1, pp. 257–264. August 17–20, Montreux, Switzerland, 1998.

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A.4 Reports

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