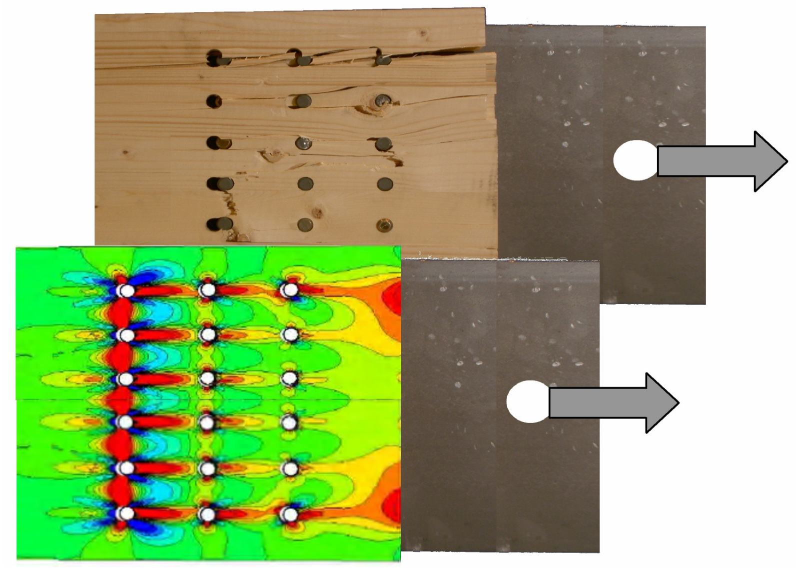


STRENGTH AND MOISTURE ASPECTS
OF STEEL-TIMBER DOWEL JOINTS
IN GLULAM STRUCTURES
– an Experimental and Numerical Study

Doctoral Thesis by
JOHAN SJÖDIN

To Jenny and Saga

To Arne and Elma

Preface

This work has been financially supported by the Wood Science Program at Växjö University (WDAT - Wood Design and Technology), the Development Fund of the Swedish Construction Industry (SBUF), the foundation CBBT ("Centre for building and living with wood") and Skanska AB. The work has also been part of a Swedish-Finish project financed by TEKES and VINNOVA. Special thanks to Moelven Töreboda Limträ AB and Setra Group AB for providing the glulam beams used in the experimental work.

First of all I want to express my deepest gratitude to four persons who, in different ways, have been more involved than others. These include my supervisor, Prof. Erik Serrano at Växjö University; Mr. Arne Emilsson at Limträteknik AB; Mr. Bertil Enquist at Växjö University and Mr Sigurd Karlsson at Skanska AB. It is most likely so that this thesis wouldn't exist if I never met these persons.

Thanks also to my former supervisors Prof. Carl Johan Johansson and Prof. Hans Petersson, for valuable opinions in connection to my work and co-authoring some of my papers. Special thanks also to Dr. Joakim Jeppsson at Skanska AB and to my colleagues at Växjö University, in particular Dr. Torbjörn Ekevid and Mr. Johan Vessby who always answered my questions.

Växjö, February 2008

Johan Sjödin

Abstract

Joints are critical parts of timber structures, transmitting static and dynamic forces between structural members. The ultimate behavior of e.g. a building depends strongly on the structural configuration and the capacity of its joints. The complete collapse of a building or other less extensive accidents that may occur usually start as a local failure inside or in the vicinity of a joint. Such serious failures have recently occurred in the Nordic countries. Especially the collapses of two large glued-laminated timber (glulam) structures clearly indicate the need of an improved joint design. The trend toward larger and more complex structures even further increases the importance of a safer design of the joints.

One aim of this partly experimentally and partly numerically based work has been to investigate if the short term capacity of steel-timber dowel joints loaded parallel to the grain is affected by an initial drying exposure. The experimental results showed that the load-bearing capacity of the joints is indeed reduced by such moisture changes. Moisture induced stresses was mentioned to be the explanation. The key point is that the climates chosen in the present work (20°C / 65% RH and 20°C / 20% RH) are equivalent to service class 1 according to EC5 (Eurocode 5 2004). Thus, EC5 predicts no decrease in load-bearing capacity, in relation to the standard climate used during testing. A decrease in load-bearing capacity in the range of 5-20%, which was found in the present work, is of course not negligible and, therefore, there could be a need to introduce the effect of drying in design codes. Because similar results were also observed for a double-tapered glulam beam, further work should consider timber structures in general.

Two numerical methods in order to predict the capacity of multiple steel-timber dowel joints loaded parallel to the grain were tested in the thesis. For the first method, where fracture mechanics (LEFM) concepts were implemented, a good correlation with the experimental results was seen. Also for the second method, where the capacity for a single dowel-type joint as given in EC5 was used as a failure criterion, a good correlation to traditional EC5 calculations of multiple dowel-type joints was seen. One advantage of using numerical methods in design is that the capacity of the joint can be calculated also for cases when the dowels are placed in more complex patterns. From both a structural and an architectural point of view this can be very important. In addition, such numerical methods are effective tools for the structural engineer when considering complicated loading situations in joints, i.e. eccentric loading giving moments in the joint.

Keywords: constraint stresses, contact-free measurement, dowel-type joints, humidity variations, glulam beams, glulam structures, linear elastic fracture mechanics, moisture-induced stresses, numerical simulations, short term capacity.

Sammanfattning

Förband är en viktig komponent i träkonstruktioner där stora statiska samt dynamiska krafter skall överföras mellan anslutande element. Konstruktionens totala lastkapacitet är starkt beroende av kapaciteten hos enstaka förband. Betydelsen av ett förbands egenskaper har aktualiserats på senare tid efter att två större limträkonstruktioner rasade i Norden under 2003.

Denna avhandling består av experimentellt samt numeriskt arbete. Ett mål har varit att undersöka om korttidskapaciteten för dymlingsförband, som belastas parallellt fiberriktningen, påverkas negativt av fuktvariationer (främst uttorkning). Resultaten från de studier som har gjorts påvisade att lastkapaciteten för dymlingsförband påverkas negativt av uttorkning. Förklaringen till dessa resultat är att fuktinducerade spänningar förekom i förbandsområdet vid belastningstillfället på grund av den föregående uttorkningen. En mindre studie har även gjorts för att undersöka om lastkapacitet för upp- och nervända sadelbalkar också påverkas av uttorkning. Resultaten ifrån denna studie påvisade liknande lastreduktion på grund av uttorkning, som konstaterats för förbanden.

Det som är intressant är att de klimat (från 20°C/65% RF till cirka 20°C/20-30% RF) som har använts i de olika studierna motsvarar den naturliga variationen i vanligt inomhusklimat, dvs. motsvarande klimatklass 1 enligt EC5 (Eurocode 5 2004) eller klimatklass 0 (eller 1) enligt BKR (Boverkets konstruktions regler 2003). Dessa konstruktionsregler tar endast hänsyn till lastvaraktighet och fuktinnehåll i en konstruktion, dvs. inte till den påvisade reduktionen av lastkapaciteten, när en byggnadsdel utsätts för uttorkning i ett torrt klimat. Baserat på resultaten som framkommit i denna avhandling, för vilka det även finns stöd för i litteraturen, finns det anledning till fortsatt forskning inom detta område. I avhandlingen föreslås att effekter enligt ovan bakas in i k_{mod} faktorn (reduktionsfaktor för lastvaraktighet och fuktinnehåll) som finns i EC5. Ett annat alternativ kan vara att betrakta fuktinducerad spänning som ett yttre lastfall.

Ett annat mål med projektet har varit att med hjälp av numeriska metoder prediktera lastkapaciteten för dymlingsförband. Två numeriska metoder har utvecklats samt testats. Med den första metoden, vilken är baserad på linjärelastisk brottmekanik, överensstämde de beräknade kapaciteterna bra med de experimentella resultaten. Även med den andra metoden, där lastkapaciteten för *en-dymlings* förband (enligt EC5) användes som ett brottkriterium i de numeriska beräkningarna, överensstämde de beräknade kapaciteterna bra med kapaciteter beräknande enligt traditionella dimensioneringsregler i EC5. Det finns flera fördelar med att införa numeriska metoder vid dimensionering av förband. En fördel är att komplicerade lastsituationer lätt kan beaktas. En annan fördel är att man kan utforma förbandet relativt fritt, med till exempel oregelbundet placerade dymlingar. Med hjälp av de traditionella beräkningsregler som används idag är detta svårt.

Contents

Paper V	**An experimental and numerical study of the effects of moisture variations and gradients in double-tapered glulam beams** Johan Sjödin and Erik Serrano Submitted to Holzforschung, February 2008.
Paper VI	**Contact-free measurements and numerical analyses of the strain distribution in the joint area of steel-to-timber dowel joints** Johan Sjödin, Erik Serrano and Bertil Enquist Holz als Roh- und Werkstoff, Vol 64, pp 497-506, 2006.
Paper VII	**An experimental and numerical study of the effect of friction in single dowel joints** Johan Sjödin, Erik Serrano and Bertil Enquist Submitted to Holz als Roh- und Werkstoff, February 2008.
Paper VIII	**A numerical study of methods to predict the capacity of multiple steel-timber dowel joints** Johan Sjödin and Erik Serrano Submitted to Holz als Roh- und Werkstoff, February 2008.

Contributions to the papers: Sjödin planned, conducted and evaluated the experimental works and the numerical works. Sjödin wrote the first versions of the papers. Opinions and changes from the co-authors were then added.

PART I:
INTRODUCTION AND OVERVIEW

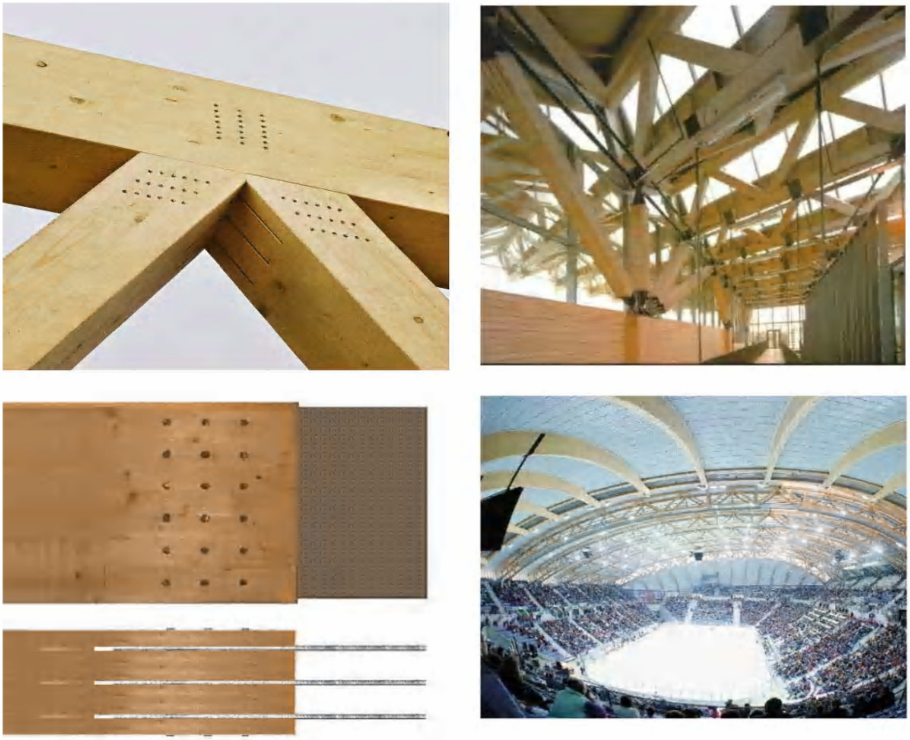
1. Introduction

1.1 Background

There are several advantages related to the use of glulam in timber structures: aesthetical reasons; the fact that glulam can be produced in a large variety of shapes giving the architect a large freedom in expression; the fire protection qualities are good if the glulam is used properly and, finally, the timber is environmentally friendly. Glulam has further an advantageous strength to density ratio, which in turn makes possible large spans, simplifies the foundation construction and facilitates the elements to be fabricated and then transported to the construction site. There are, however, also some drawbacks in terms of using glulam instead of other materials, and these have to be paid some attention. Most of these drawbacks relate to the properties of the wood material, and include for example: low tensile capacity perpendicular to the grain; large variability of strength and stiffness properties; large influences of moisture and moisture changes and, finally, the inhomogeneous nature of the material due to e.g. the presence, of knots and the associated deviation in grain.

Dowel-type joints, which are the main subject of this thesis, are important elements in glulam structures. Their task is to connect different structural members to each other in order to form, for example, roof trusses of different kind, Figure 1. Dowel-type joints are one of the most common types for glulam structures. These comprise nails, screws, staples, drift pins, threaded rods or bolts (Blass, 2003). In the dowel-type joints studied here, the elements involved are connected by steel plates and steel dowels, Figure 1a.

The complex behavior of dowel-type joints is very much related to the complex structure of wood. Adding to this the complex loading situation in a timber truss, the design of dowel-type joints is crucial. Mistakes in the design phase or during the erection phase can easily affect the capacity of the joint and the entire structure. Telling arguments of that are the collapses of two larger glulam structures in the Nordic countries that occurred a few years ago where the joints, more or less, were the primary reasons for the collapses (Frühwald et al 2007; Ranta-Maunus and Kevarinmäki 2003). One of the collapses was an exhibition hall in Jyväskylä, Finland, where 2500 square meter of the roof fell down one month after the inauguration (Figure 2a). The other structure that collapsed was a bicycle arena in Ballerup, Denmark, where approximately one third of the roof structure collapsed (Figure 2b).



(a) (b)

Figure 1 (a) Dowel-type joints with steel plates and steel dowels. (b) Two glulam structures in which dowel-type joints are used. The pictures are reproduced by the permission of Svenskt Limträ AB (www.svensktlimtra.se).

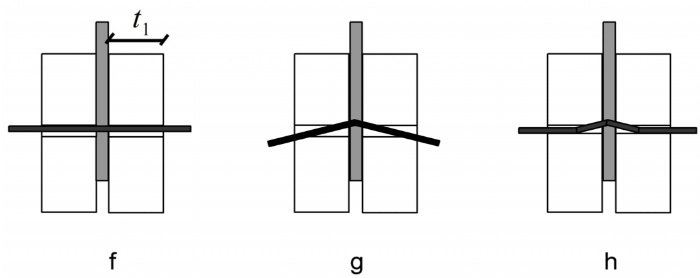
(a) (b)

Figure 2 (a) The exhibition hall in Jyväskylä, Finland and (b) the bicycle arena in Ballerup, Denmark.

1.2 Dowel-type joints loaded parallel to the grain

In the thesis, only loads parallel to the grain have been considered for the dowel-type joints studied. Thus, such load condition is considered below.

1.2.1 Design and characteristics



$$f_{v,RK} = \min \begin{cases} f_{h0k}\, t_1\, d & \text{f} \\ f_{h0k}\, t_1\, d \left[\sqrt{2 + \dfrac{4 M_y}{f_{h0k}\, d\, t_1^{\,2}}} - 1 \right] & \text{g} \\ 2.3 \sqrt{M_y f_{h0k}\, d} & \text{h} \end{cases}$$

Figure 3 Possible failure modes for a dowel joint loaded parallel to the grain in which a steel plate is inserted in a slot in the wood. The equations presented are similar to those included in Eurocode 5 (2004).

Design rules for dowel-type joints loaded parallel to the grain are generally based on Johansen´s yielding theory (Johansen 1949), where perfect plasticity of both the dowels and the timber is assumed. In EC5 (Eurocode 5, 2004) several failure modes are given. The possible failure modes for a dowel-type joint loaded parallel to the grain in which a single steel plate is inserted in a slot in the timber are presented in Figure 3 together with equations associated with them. Here t_1 stands for the thickness of the timber, d for the diameter of the dowels, f_{h0k} for the embedment capacity of the timber parallel to the grain and M_y for the bending capacity of the dowels. Different restrictions have been adopted in EC5 in an effort to adapt Johansen´s yielding theory to real situations. The reason for this is, among other things, that the load-bearing capacity of multiple dowel-type joints divided by the number of dowels is not equal to the load-bearing capacity of a single dowel. This is due to the load distribution among the dowels being non-uniform and that joints of this type tend to show brittle failure modes, before the load-bearing capacity of individual dowels is reached, Figure 4. This has been studied in several investigations concerned in particular with multiple dowel joints involving a single row of dowels loaded in tension parallel to the grain, see e.g. Cramer (1968), Lantos (1968), Isyumov (1967), Wilkinson (1986) and Jorissen (1998, 1999). The findings of these and other studies have led to the placements of the dowels being restricted and to the total number of dowels in the load direction being reduced to an effective number of dowels as is given in EC5. In addition, the current version of EC5 contains informative design rules aimed at reducing occurrence of the block-shear/plug-shear failure mode at which attention has been directed in recent investigations; see Hanhijärvi et al. (2006).

Despite the fact that the joints are designed according to design codes, several experimental investigations on dowel-type joints report sudden and brittle failures, see (Siem 1999; Quenneville 1997; Quenneville and Mohammad 2000; Pedersen et al. 1999). Such behavior is, despite of the fact that informative design rules exist today in order to avoid it, an unpleasant characteristic of dowel type joints where a ductile behavior should be preferred in order to increase the safety of the joint and the structure as a whole.

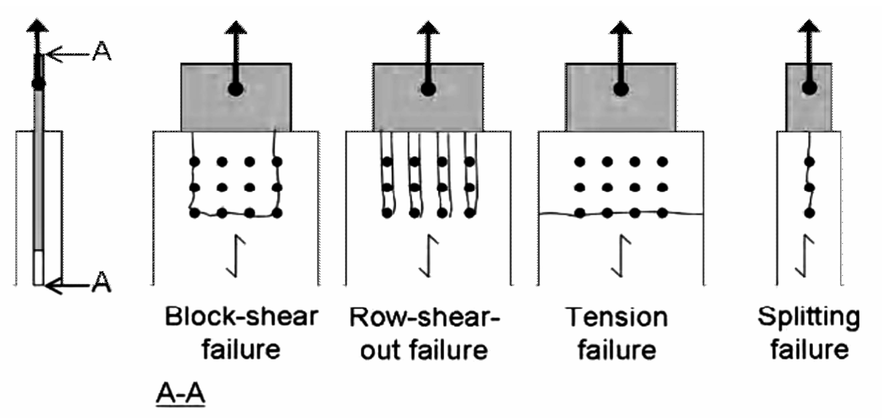


Figure 4 Expected final failure modes for multiple dowel joints loaded in tension parallel to the grain.

1.2.2 Effects of different configurations

How the joint configuration, material properties, numbers of dowels, etc. influence the behavior of multiple dowel-type joints loaded parallel to the grain has been studied in investigations by use of both theoretical and experimental methods. For joints with a single row of dowels placed in the load direction parallel to the grain, extensive work has been carried out, as already indicated. Jorissen (1998, 1999), for example, concluded that the number of fasteners, the spacing between them in the load direction and the slenderness ratio are the most important parameters for dowel-type joints loaded in tension parallel to the grain. Jorissen showed both theoretically and experimentally that increasing the spacing between the dowels in the load direction led to the load-bearing capacity being increased and brittle tendencies being avoided to a greater extent.

Experimental work on dowel-type joints having several dowel rows perpendicular to the grain has been carried out in Canada (Quenneville, 1997; Quenneville and Mohammad, 2000). It was found, for example, that reducing the distance between the end grain and the first dowel column leads to the load-bearing capacity being reduced and the row-shear-out failure mode (Figure 4) being more prominent. It was also concluded that the thickness of the side members of the timber (t_1 in Figure 3) affected the joint behavior, not only their load-bearing capacity, as expected, but also the failure mode. Increasing the thickness generated block-shear failure, whereas the row-shear-out failure mode was more prominent when the thickness was smaller. An interesting observation made was that the spacing between the dowel rows perpendicular to the grain affected both the load-bearing capacity and the failure mode. When the distance between the dowel rows was increased, the load-bearing capacity likewise increased and the failure mode changed from the block-shear failure to the row-shear-out failure mode.

1.3 Effect of moisture variations and gradients

According to e.g. Dinwoodie (2002), both the strength and the stiffness of timber depend on the MC (moisture content) of the timber. A decrease of the MC usually corresponds to an increase of the strength of the timber. The same tendencies are expected for joints, and this has also been shown in experimental studies of small-scale timber joints (see e.g. Rammer and Winistorfer 2001; Rammer 2001). However, it has also been shown that the short term capacity of structural timber members can be negatively affected when the timber is exposed to moisture variations in time and moisture gradients within the member. Such influence has been seen for notched beams, prismatic glulam specimens loaded perpendicular to the grain and curved beams (Gustafsson et al. 1998; Jönsson and Thelandersson 2003; Aicher et al. 1998). Stresses induced by moisture gradients are usually mentioned to be the explanation of the results, see Jönsson (2004, 2005).

For dowel-type joints loaded parallel to the grain, few results exist in the literature where the short term effects of moisture variations and gradients have been studied. For dowel-type joints loaded perpendicular to grain, however, some results exist in the literature (see Gustafsson and Larsen 2001; Larsen and Gustafsson 2001). The results in those studies did not reveal any major influence of moisture variations for the joints tested. The reason for this can be the loading angle and/or that only small-scale joints were tested. For multiple dowel-type joints with dowels placed in several rows and columns there is a risk that the constraint stresses, see Figure 5, will be higher than for small-scale joints with, say only two dowels placed close to each other, perpendicular to the grain. In addition, moisture changes induce rather high stresses in glulam members due to moisture gradients (Jönsson 2004, 2005). As dowel-type joints can facilitate a high degree of moisture transport – due to the end grain usually being exposed and the existence of slots for the steel plates (Figure 6) – there is a risk that high internal stresses can be present in the joint area. *The hypothesis in this work is that such moisture induced stresses can affect the short term capacity of multiple steel-timber dowel joints loaded parallel to the grain.*

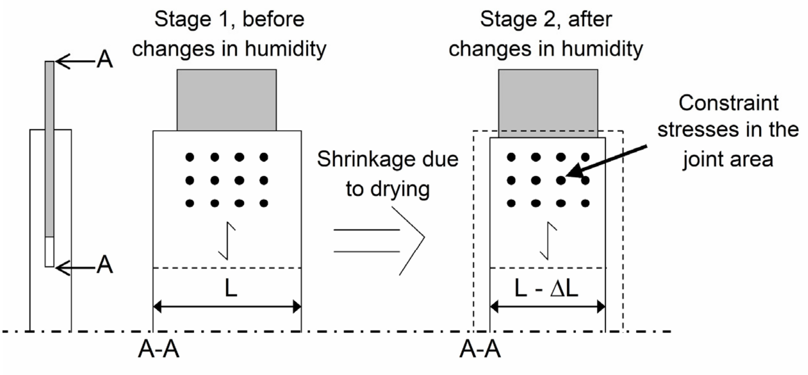


Figure 5 Constraint stresses caused by the moisture-induced deformations being restrained by the dowels, which are fixed in position by the steel plate.

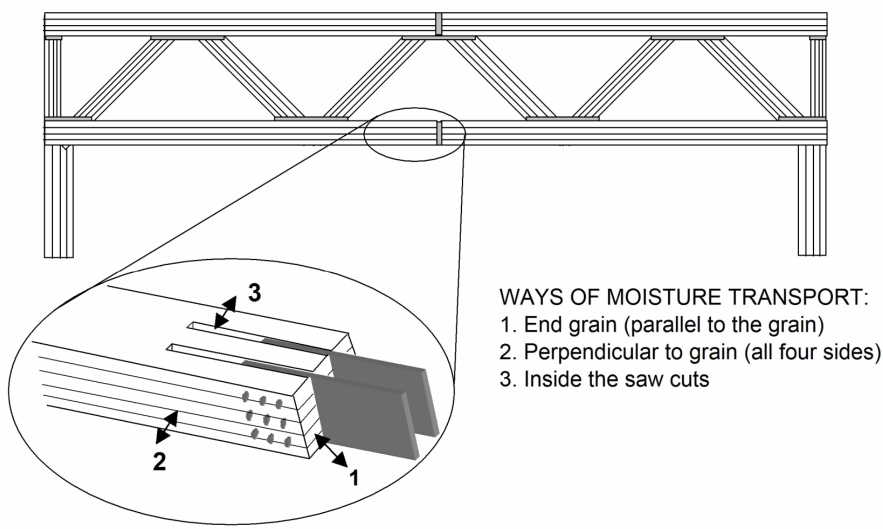


Figure 6 Ways of moisture transport in a steel-timber dowel joint.

2. Overview of the Present Work

2.1 Aims and Limitations

The present work has been carried out with focus on experimental and theoretical methods. The perspective has been from a structural engineering point of view where the overall aim has been to increase the knowledge about the mechanical behavior of dowel-type joints. More precisely, this work has had the following two aims:

1. *Verify the hypothesis presented at the end of chapter 1.3: stresses induced by moisture variations can affect the short term capacity of multiple steel-timber dowel joints loaded parallel to the grain.*

2. *Predict the short-term capacity of multiple dowel-type joints by use of numerical methods.*

The limitations of the thesis include the fact that only steel-timber dowel joints and inverted, double-tapered glulam beams have been studied. In addition, the joints were, as mentioned in chapter 1.2, only loaded in tension parallel to the grain. Although the long-term capacity of joints is important, little attention is directed at this in the study, the short-term capacity of the joints being of major interest.

2.2 Methodology and outline of the papers

The thesis consists of eight papers, appended in Part 2, covering the aims stated above. This section gives a brief outline of the content of the papers and their respective contributions to the aims.

Papers I to IV present experimental and numerical results of the effect of moisture variations for steel-timber dowel joints loaded parallel to the grain. Thus, those papers concern aim 1 presented above.

Paper V presents experimental and numerical results of the effect of moisture variations for inverted, double-tapered glulam beams. The overall aim of this paper was to show that not only joints are affected by moisture variations and gradients.

Paper VI presents experimental and numerical results concerning strain distributions in the joint area of multiple dowel-type joints loaded in tension. The aim of this paper was to verify the strain distribution obtained in the numerical simulations by use of a contact-free measurement system and to evaluate the measurement system itself. The knowledge gained in this study was later used in the study presented in Paper VII.

Paper VII presents experimental and numerical results concerning the effect of friction between the dowel and the surrounding timber for single dowel-type joints. The aim of this paper was to use this simple joint type to elaborate a theoretical model to be used to predict the capacity of multiple dowel-type joints.

Paper VIII presents two numerical methods to predict the capacity of multiple dowel-type joints. Thus, this paper concerns aim 2 presented above.

2.3 Experimental Methods

2.3.1 Specimens

The specimens tested are presented in Figure 7 and 8. The different configurations were decided in close corporation with representatives of the Swedish glulam industry in order to assure that the tests were of interest for the practicing engineer. Norway spruce and Scots pine were used for the smaller timber specimens. For the larger specimens, spruce glulam beams were employed. The dowel placement for the joints was usually set according to the minimum requirements as given in EC5 (Eurocode 5, 2004). The diameter of the dowels was set to either 12 or 20 mm. The holes in the slotted-in steel plates were cut out by laser. In order to drill the holes in the timber, the steel plates were used as templates.

The moisture content and the density for the timber were determined according to ISO 3130 (1975) and ISO 3131 (1975) respectively. All specimens, except one group of specimens in Paper I, were initially stored in a standard climate of 20ºC and 65% relative humidity (RH) until the equilibrium moisture content was reached, prior to further preparation.

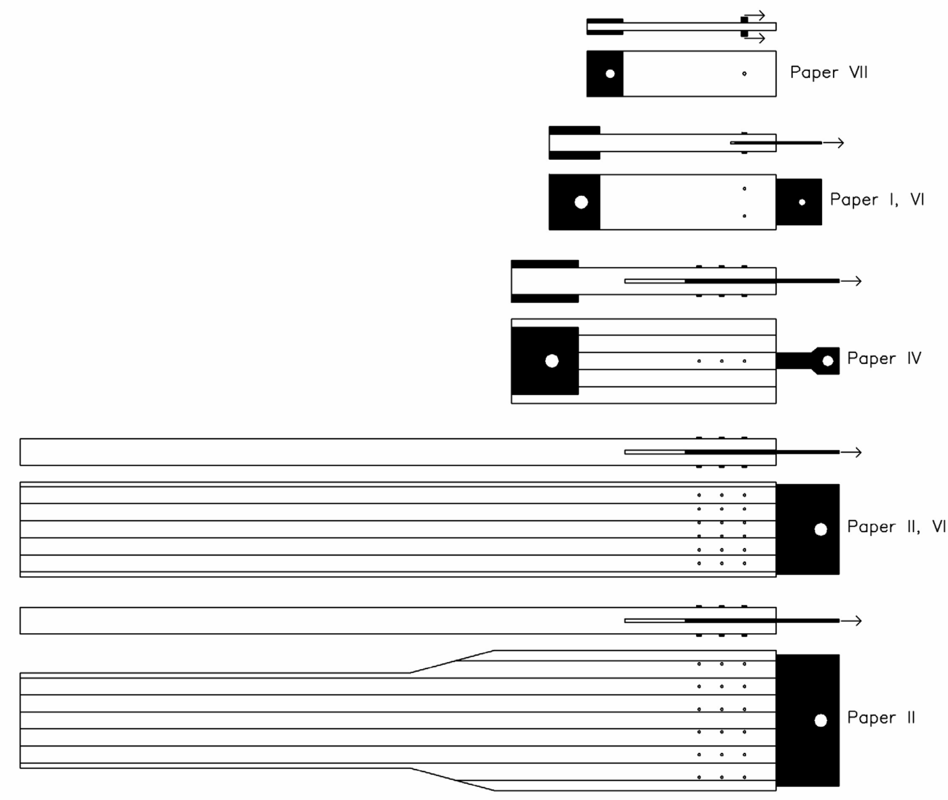


Figure 7 All joint specimens tested. The different geometric setups are drawn to scale in proportion to each other.

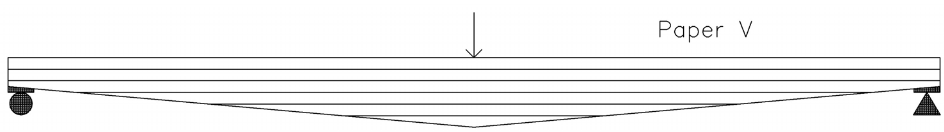


Figure 8 The type of beam specimen tested in paper V.

2.3.2 Test conditions in order to study the effect of moisture variations and gradients

(a) (b)

Figure 9 (a) Storage of joint-specimens in climate chambers (observe that for the specimens below the dowels and the plate are not fitted yet) and (b) a moisture induced crack in a joint-specimen exposed only to drying

In order to study the effects of moisture variations and gradients, the specimens of each type were divided into different categories. The categories differed with respect to the climatic conditions employed and, for the joint specimens, also with respect to when the steel plate and the dowels were fitted into the joints (Figure 9a). Typical characteristics for the test conditions of the joint specimens (similar were used for the beam specimens) are summarized into three categories:

- For category A, the reference category, the steel plate and the steel dowels were fitted into the specimens when a 12% equilibrium moisture content had been reached in a 20ºC, 65% RH climate, after which the specimens were loaded to failure.
- For category B, the climate conditions were somewhat drier. After an equilibrium moisture content of 12 % had been reached, the specimens were stored at 20ºC, 20 or 30% RH, their being kept in this climate then for several days before the steel plate and the steel dowels were fitted into them. The specimens were then loaded to failure.
- For category C, the steel plate and the steel dowels were fitted into the specimens when an equilibrium moisture content of 12% had been reached. The climate was then changed from the initial climate of 20ºC, 65% RH to one of 20ºC, 20-30% RH. This climate was kept for several days before the specimens were loaded to failure.

The climate conditions for category A were chosen to simulate standard procedures used in the testing of joints and to employ the results obtained for this category as a reference.

The climate change for categories B and C was chosen to simulate a reasonably realistic change in climate. Nordic glulam beams are normally delivered from the manufactures with an MC of about 12 %, corresponding to the standard climate of 20ºC, 65% RH used in the present study. Climate data for heated massive timber structures during the winter, presented by (Ranta-Maunus 2003), supports the choice of 20ºC and 20-30% RH.

During storage in the climate chambers, measurements and visual observations were made continuously in order to study direct moisture effects, e.g. cracks (Figure 9b), deformations etc.

2.3.3 Loading procedure

After being stored in climate chambers, all specimens were loaded to failure. For the joint specimens a fork connection was used to connect the dowel/steelplate to the loading machine, Figure 10. For the small scale joints, the other end was first reinforced with plywood and was then connected to a similar fork. For the large scale joints, a wedge device was used for the other end, where the specimens were inserted about 1m into the grip of the testing machine (Figure 10). To avoid eccentricity due to the fixed connection to the wedge device, the joints were centered carefully. The 3-point bending test set-up used for the beam specimens is shown in Figure 10.

During the loading procedure, all the specimens were subjected to a displacement-control rate in order to reach failure within 5-15 minutes. During the tests, the load was recorded and the displacements were normally measured by inductive gauges.

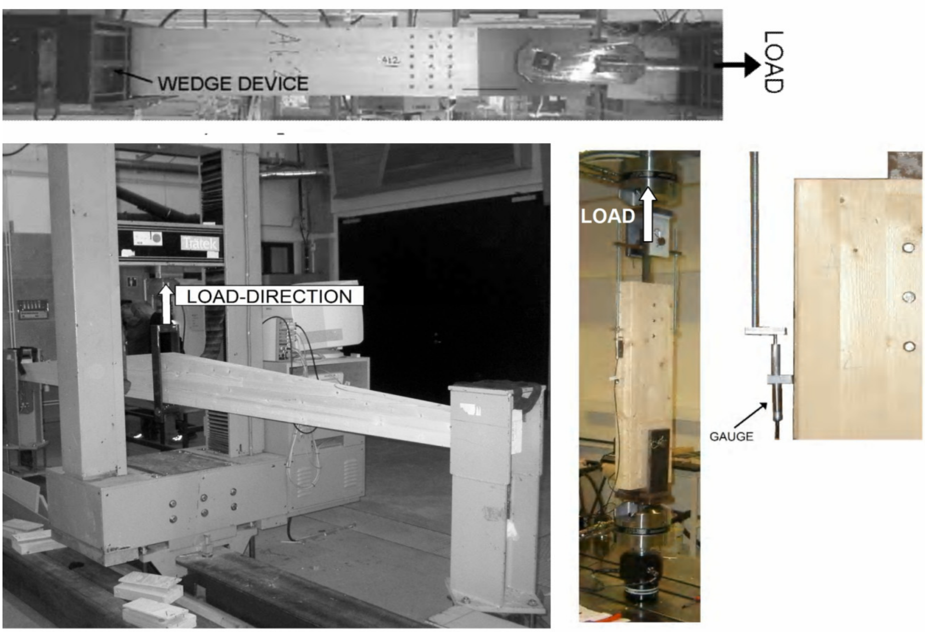


Figure 10 Loading-arrangement for the specimens.

2.3.4 Contact-free measurements

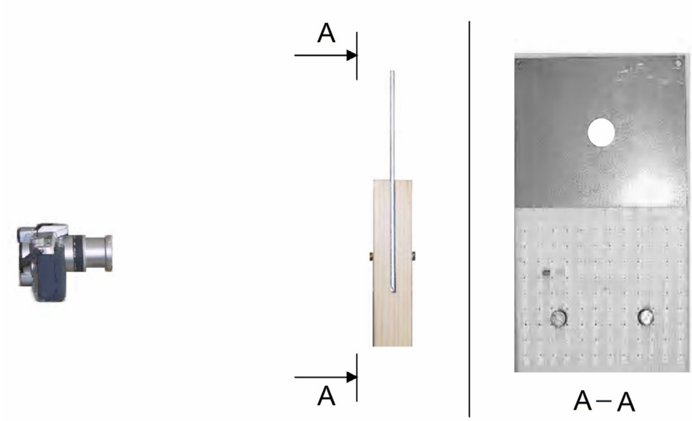


Figure 11 Contact-free measurement arrangements in Paper I.

In Paper I, the strain-distribution during conditioning was studied using a contact-free measurement technique. The technique employed in testing was similar to those presented in (Jeppsson 2001; Jönsson and Svensson 2004). Pictures of a dotted area were taken at various times by means of a digital camera (Figure 11). The pictures were then processed using a Matlab-code (Austrell et al. 1996). The relative displacements between the dots in a sequence of pictures were calculated and were converted to strains. In the present study only the strains perpendicular to grain and the shear strains in the area around the dowels were determined.

The camera used in the study had a relative high resolution, one of 2560x1920 pixels, which was valuable since small displacement differences had to be calculated from the values measured. A fixture was built allowing the specimens to be fixed at the same position each time pictures were taken. The area considered was limited to 130x110 mm^2 in size. In order to obtain a high contrast, the black dots were placed on a white background. The distances between the dots were set to 12 mm and one pixel corresponded to a length of approximately 1/20 mm. In order to estimate the measurement error, several pictures of the same object were taken. The measurement uncertainty was estimated to ¼ pixel, which corresponds to an accuracy of the strain perpendicular to grain of approximately ±0.002.

In Papers VI and VII a commercial contact-free measurement system, ARAMIS™ manufactured by the company GOM, was employed in order to study the strain distribution in the joint area during loading. The system is based on evaluating a random or regular pattern, which is applied to the surface and deforms along with the material. The placing of two CCD cameras (1280 by 1024 resolution) in front of the specimen at different angles enables stereoscopic pictures of the patterned surface to be taken, Figure 12. The first digital-image processing step defines macro-image facets in the image pair taken at the original, unloaded state. For each stage of loading, the 3D coordinates of these facets on the specimen's surface are calculated accurately using image correlation and photogrammetric principles. On the basis of these 3D coordinates, the 3D displacements and in-plane strains can be calculated with a high degree of spatial resolution.

The test arrangements for all the joints were similar. The CCD cameras were calibrated to a measurement volume that included the joint area. A random pattern was achieved in two steps. First a matt light-colored paint was sprayed on the area around the dowels/dowel. This was done in order to obtain better contrast of the gray scale defining the facets and also to reduce the shininess of the timber. After this, small black dots were applied by spraying black paint at the surface from a distance.

The cameras were triggered, typically every five seconds, also logging analog signal readings of displacement and force from the loading machine. The images taken during testing were then processed by the software included in the ARAMIS-system. For each pair of images, 3D coordinates for a large number of facets could be determined together with the corresponding strains. The measurement uncertainty, i.e. the strain accuracy, was, according to the manufacturer, approximately 0.01%.

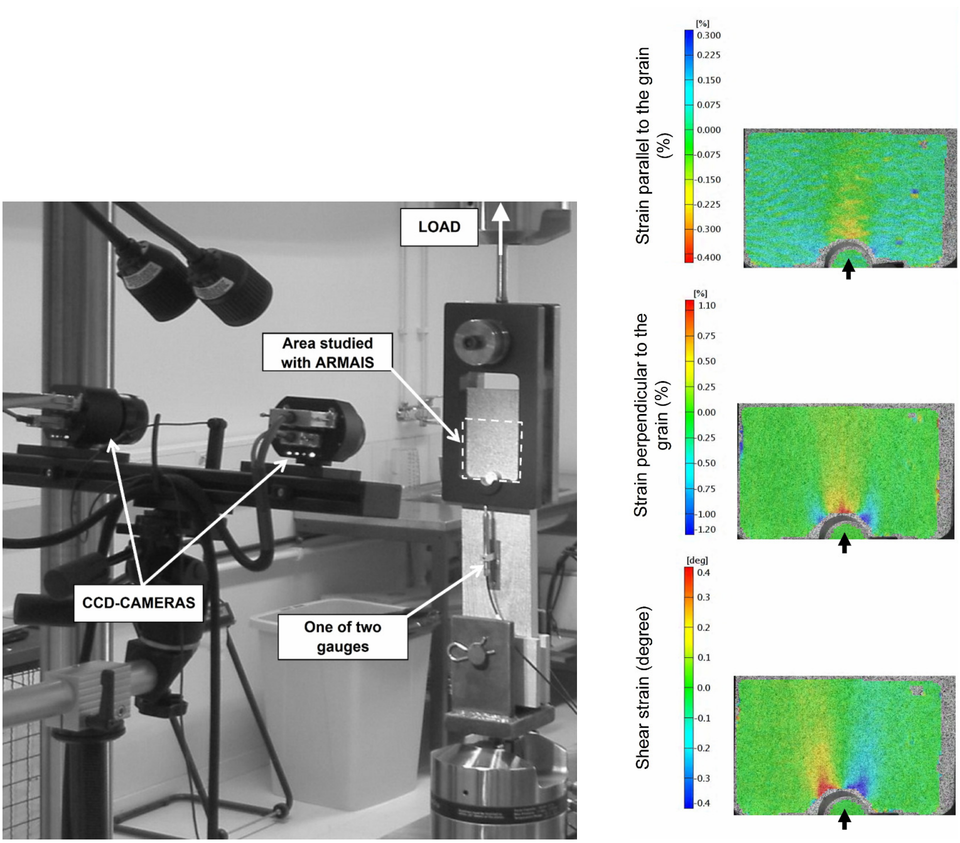


Figure 12 Contact-free measurement arrangements in Paper VII and some results.

2.4 Numerical Methods

2.4.1 General assumptions

The FE-software ABAQUS (ABAQUS Inc., 2003, 2004) was used for the numerical analyses performed in the thesis. For all simulations, linear-elastic behavior was assumed for the wood. The elastic properties and the Poisson's ratios for defining the orthotropic wood material were estimated either from the European standards (1999, 2004) or from Dinwoodie (2002). In general, no consideration was taken of the difference between the radial and the tangential direction of timber.

Linear-elastic behavior was assumed also for the steel plates and the steel dowels in the simulations. The modulus of elasticity and Poisson's ratios were set to E=210000 MPa and v=0.3, respectively. The interaction between the dowels and the surrounding timber was modeled by contact elements (included in the FE-software) involving friction in the tangential direction of the dowels.

2.4.2 Transient moisture flow simulation and related deformations and stresses

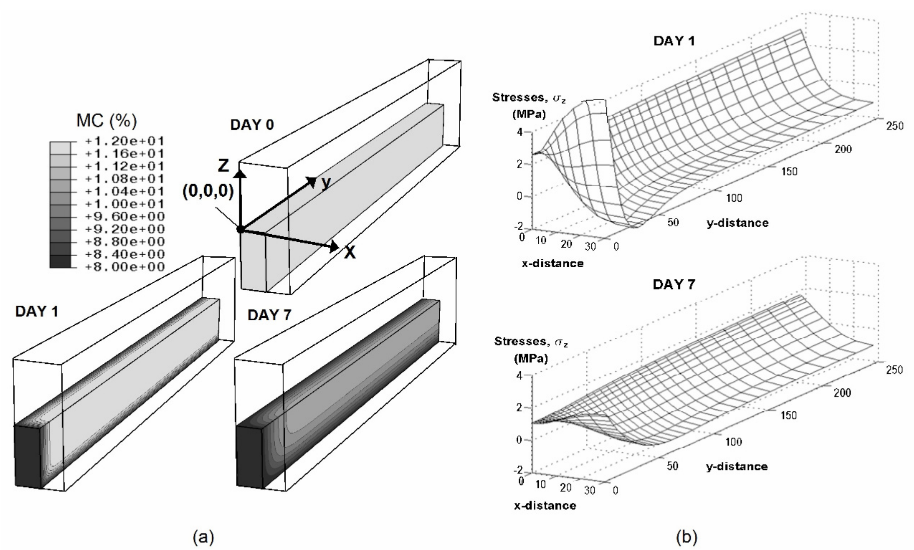


Figure 13 Result from Paper III: Changes in MC of a glulam beam (60·150·700 mm3) during drying from 65% RH to 20% RH and belonging stresses perpendicular to the grain presented on the symmetry surface.

The model employed in order to simulate the stresses induced by moisture gradients involved two types of simulations; first one transient moisture flow simulation was performed, followed by a simulation of the moisture-induced deformations and stresses.

The transient moisture flow simulation has been performed by taking advantage of the analogy of transient heat flow simulations. The fundamental equation to solve using the FE-software is, for the case of one dimensional transient heat flow, given by:

$$c\rho \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\lambda(T) \frac{\partial T}{\partial x} \right) \tag{1}$$

where T is the temperature, c is the specific heat, ρ is the timber density and λ is the thermal conductivity. Dividing Eq. (1) by c and ρ results in (assuming constant density and specific heat):

$$\frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(\frac{\lambda(T)}{c\rho} \frac{\partial T}{\partial x} \right) \tag{2}$$

By setting the values of the specific heat and the timber density to 1, and setting the value of the thermal conductivity equal to the coefficient of diffusion, we obtain the differential equation governing one dimensional transient moisture flow:

$$\frac{\partial u}{\partial t} = \frac{\partial}{\partial x}\left(D_w(u) \frac{\partial u}{\partial x} \right) \tag{3}$$

Here, D_w is the coefficient of diffusion of wood and U is the moisture content (MC). Thus, for the two- or three-dimensional case, the temperature and the constitutive matrix containing the thermal conductivities are replaced by the moisture content as the primary variable and the matrix containing the coefficients of diffusion, respectively.

The timber was assumed to have an initially uniform MC of 12% (corresponding approximately to a climate of 65% RH at 20°C) and was then subjected to a climate of 20% RH in order to simulate the drying phase. The MC of the timber surface was assumed to be in equilibrium with the surrounding air. The diffusion coefficients, assumed constant and not changing with neither MC nor temperature, were set to $D_R = D_T = 4 \cdot 10^{-10}$ m^2/s in the cross-grain directions and $D_L = 13 \cdot 10^{-10}$ m^2/s in the longitudinal direction, Eriksson (2005). These values correspond to values typical for Norway spruce at 20 ºC.

In the simulation of the moisture induced deformations and stresses, constant shrinkage coefficients α of the timber were used. The values chosen were $\alpha_L = 0.0001$ in the longitudinal direction and $\alpha_T = 0.002$ in the cross-grain direction and are typical for Norway spruce as given in timber engineering handbooks, see e.g. Carling (2001).

Thus, a general assumption made is that all the material properties used in the calculations were assumed to be constant and not changing with changing MC. During a drying exposure an increase of stiffness properties and strength values should be expected for timber (Dinwoodie 2000; Ormarsson 1999).

2.4.3 Fracture analyses

Different models may be used for fracture analyses of timber structures. In this thesis two approaches, both based on linear elastic fracture mechanics (LEFM) concepts, were used. These are briefly described below.

2.4.3.1 Energy release rate approach

The basic concept of this method is that the energy release rate, G (J/m^2), i.e. the energy released during the propagation of a pre-existing crack is calculated. For each crack length, a critical value of the applied forces can be calculated, corresponding to the load giving an energy release rate G equal to the critical energy release rate G_c. G_c is assumed to be a material parameter. For structural elements, loaded by only a single external load during quasi-static conditions, a common expression (see e.g. Daudeville and Yasumura 1996; Davenne et al. 1996; Aicher et al. 2002; Serrano and Gustafsson 2006) in order to evaluate G is given by:

$$G(a) = \frac{-\partial \Pi}{t\, \partial a} = \frac{P^2}{2t}\frac{\partial C}{\partial a} \quad , \quad C = \delta / P \tag{4}$$

where $d\Pi$ denotes the change of potential energy, da the extension of the length a of the crack, δ the displacement of the structure at the load application point, t the specimen width and P the load acting on the structure. Figure 14a gives an example of how the energy release rate G is calculated for a notched beam.

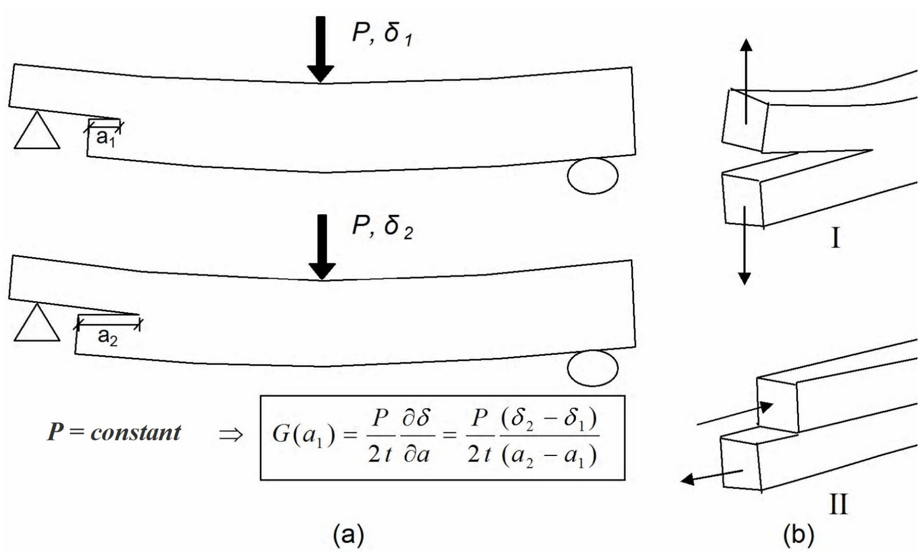


Figure 14 (a) An example of how to calculate the energy release rate G of a notched glulam beam and (b) definition of the modes of loading and fracture relevant for this work.

One difficulty in the analysis is that G_c depends on the mode of cracking. In this thesis a combination of mode I (opening mode) and mode II (in-plane shear mode) was expected (Figure 14b), i.e. the critical energy release rate G_c is calculated as:

$$G_c = G_I + G_{II} \tag{5}$$

In order to consider the mixed mode of fracture, a concept presented in e.g. Petersson (2002) was adopted. The degree of mixed mode is calculated by the average value of the ratio between the shear and normal stresses (with respect to the crack plane) along a certain length ahead of the crack tip.

The crack propagation criterion used for mixed-mode fracture is the so-called Wu-criterion, the same as adopted by Petersson (2002). In terms of stress intensity factors this reads:

$$\frac{K_I}{K_{Ic}} + \frac{(K_{II})^2}{(K_{IIc})^2} = 1 \tag{6}$$

which in terms of energy release rates can be expressed as

$$\frac{\sqrt{G_I}}{\sqrt{G_{Ic}}} + \frac{G_{II}}{G_{IIc}} = 1 \tag{7}$$

In Eq. (6)–(7), the indices *I* and *II* correspond to the current stress intensity (energy release rate) in mode I and II while indices *Ic* and *IIc* correspond to the critical stress intensity (energy release rate) in pure mode I and II respectively. After some manipulations, see Petersson (2002), the critical energy release rate G_c in mixed mode can be expressed as

$$G_c = \frac{1}{a}\left[1 + \frac{b^2}{2a}\left(1 - \sqrt{1 + \frac{4a}{b^2}}\right)\right] \tag{8}$$

where

$$a = \frac{1-\kappa^2}{G_{IIc}} \tag{9}$$

$$b^2 = \frac{\kappa^2}{G_{Ic}} \tag{10}$$

and

$$\kappa^2 = \frac{1}{1 + \sqrt{\frac{E_T}{E_L}\left(\frac{\overline{\tau}}{\overline{\sigma}}\right)^2}} \tag{11}$$

with G_{Ic} and G_{IIc} denoting the critical energy release rates in mode I and mode II respectively, E_L and E_T denoting the elastic moduli in the longitudinal and the tangential direction of the timber respectively, and $\overline{\tau}/\overline{\sigma}$ denoting the ratio between the average shear and normal stresses. In Figure 15 results from Paper V are presented, where for example G_c=$G_{c,12mm}$ means that the ratio between the average shear and normal stresses is based on a summation over a length of 12 mm.

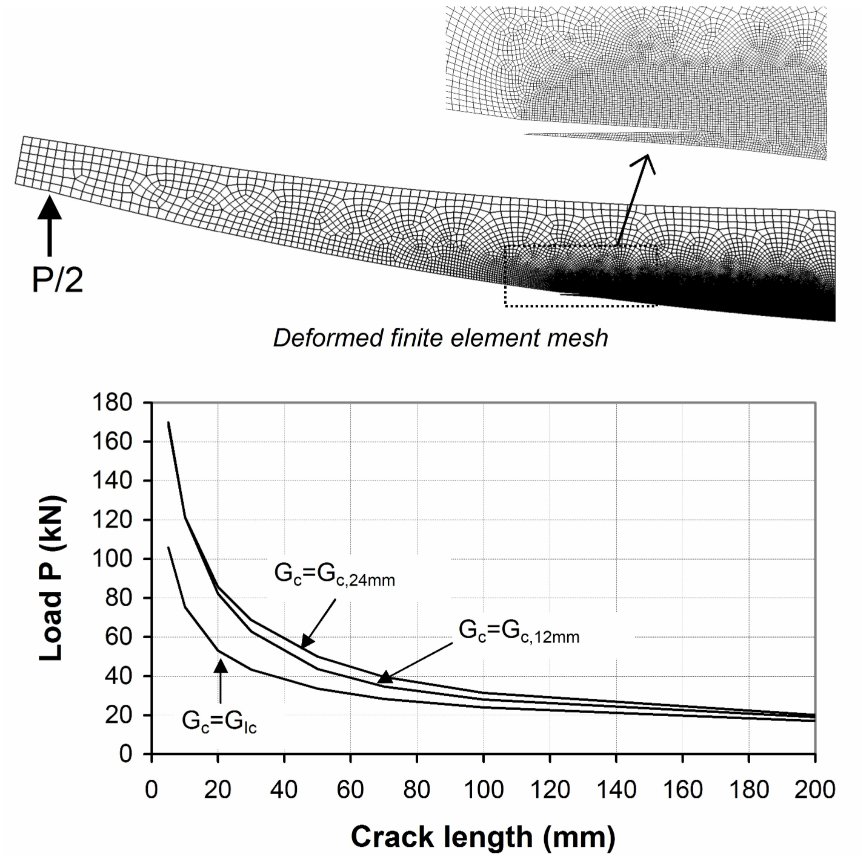


Figure 15 Relation between crack load, initial crack length and various choices of G_c of an inverted double-tapered glulam beam. Calculations are based on the energy release rate approach.

2.4.3.2 Mean stress approach

The basic concept of this method is to evaluate the mean stresses acting across an area of a size that is governed by the properties of the material (Gustafsson 2002). A stress criterion is then used to evaluate the capacity. The criterion used in this thesis is given by

$$\left(\frac{\bar{\sigma}}{f_t}\right)^2 + \left(\frac{\bar{\tau}}{f_v}\right)^2 \leq 1 \tag{12}$$

where f_v is the longitudinal shear strength of the timber material, f_t is the tensile strength (here in the tangential direction) of timber and $\bar{\tau}$ and $\bar{\sigma}$ are the corresponding mean shear stresses and mean normal stresses acting across a possible fracture area (Gustafsson 2002). The fracture area is set equal to the width of the timber specimen times a certain length (x_0) in the longitudinal direction. The length (x_0), which corresponds to the mean stress length, was calculated according to

$$x_0 = \frac{2}{\pi} \frac{E_I G_{IC}}{f_t^2} \frac{E_L}{E_T} \left(\frac{G_{IIC}}{G_{IC}}\right)^2 \frac{1}{4k^4} \left\{ \sqrt{1 + 4k^2 \sqrt{\frac{E_L}{E_T} \frac{G_{IC}}{G_{IIC}}}} - 1 \right\}^2 \left\{ 1 + \frac{k^2}{(f_v / f_t)^2} \right\} \tag{13}$$

where

$$\frac{1}{E_I} = \frac{1}{E_L} \sqrt{\frac{E_L}{2E_T}} \sqrt{\sqrt{\frac{E_L}{E_T}} + \frac{E_L}{2G_{LT}} - \nu_{TL} \frac{E_L}{E_T}} \tag{14}$$

and

$$k = \bar{\tau} \,/\, \bar{\sigma} \quad \text{(i.e. mixed mode ratio)} \tag{15}$$

with E_L, E_T, G_{LT}, ν_{TL}, denoting the elastic properties of timber, G_{IC} and G_{IIC} the fracture energy for pure mode I and mode II cracking, respectively and f_v and f_t the strength properties of timber as mentioned above (Gustafsson 2002). The definition of the length x_0 is such that the failure criterion gives the same load carrying capacity as that predicted using classical LEFM for a body of brittle material and containing a sharp crack.

The theoretical background of Eq. (13)–(15) (see Gustafsson 2002; Serrano and Gustafsson 2006) are related to the same fundamental equations of LEFM that the energy release rate approach is based upon. Due to that, similar results as presented for the beam in Figure 15 for different initial crack lengths should be expected when using the mean stress method. In Figure 16 this is indicated by the numerical results obtained using the energy release rate approach as well as results obtained using the mean stress approach.

The mean stress approach was used in order to predict the load-bearing capacity of both single dowel joints (Paper VII) and multiple dowel joints (Paper VIII). Good correlations to experimental results were found in both these papers, see e.g. Figure 17.

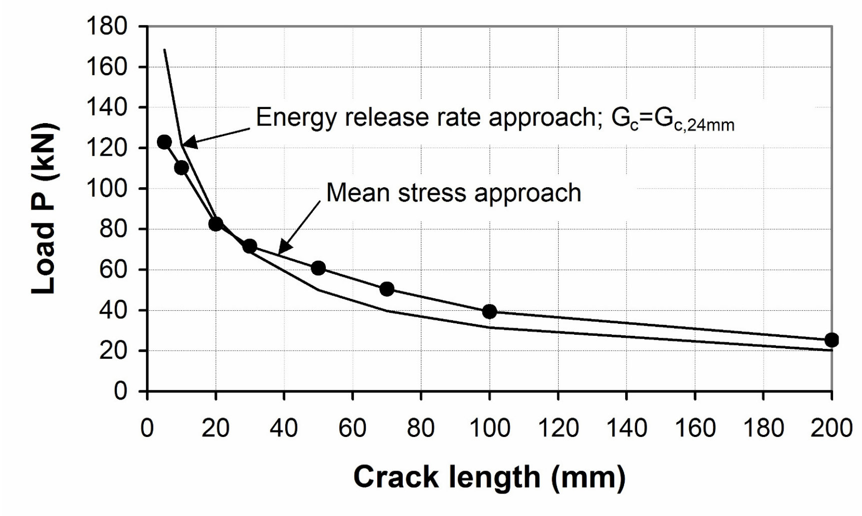


Figure 16 Relation between crack load and initial crack length of an inverted double-tapered glulam beam. Calculations are based on the energy release rate approach and the mean stress approach.

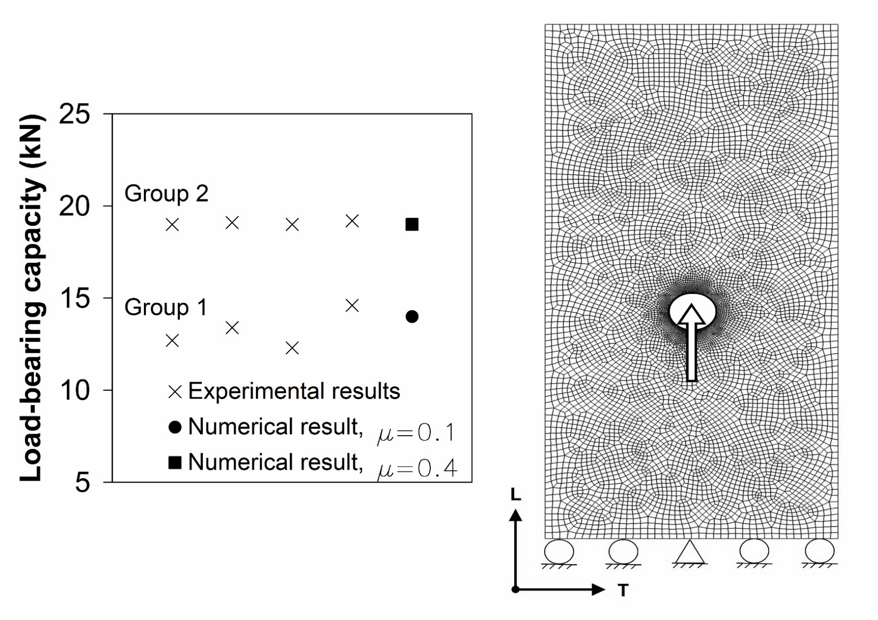


Figure 17 Load-bearing capacity of single dowel joints. Numerical and experimental results for different dowel surfaces. For group 1, the dowels had a smooth surface and for group 2, the dowels had a rough surface.

2.5 Concluding remarks and future work

2.5.1 Summary of appended papers

Papers I and II present experimental results concerning the influence of initial moisture-induced stresses in the joint area in dowel-type joints loaded in tension parallel to the grain. The moisture induced stresses were mainly seen as being induced due to the shrinkage deformations being restrained perpendicular to the grain by the fasteners in the joints. In paper I, in which small-scale joints were studied, no major influence on the load-bearing capacity could be detected for the joints being initially exposed to this condition. In contrast to paper I, a significant decrease in load-bearing capacity (20-25% decrease if comparing to reference joints not exposed to drying), under similar conditions, was detected for the large-scale joints reported in paper II.

An observation of interest made in paper II and also verified in paper IV was that the load-bearing capacity of joints initially exposed to drying, without the steel plate and dowels fitted to the joints, decreased in comparison to reference joints not exposed to drying. Stresses caused by moisture gradients are the explanation to this effect. Numerical results presented in paper III confirm this explanation.

An interesting observation was also made in paper V. It was found that the load-bearing capacity of inverted, double-tapered glulam beams is negatively affected when the timber is exposed to drying. The influence of drying resulted in a decrease of the mean load-bearing capacity of 5-10% as compared to reference beams not being exposed to drying. By numerical simulations it was shown that stresses induced by moisture gradients interact with stresses from mechanical loads, in the area where the final failure mode usually was initiated. Numerical simulations based on linear elastic fracture concepts further confirmed the findings of a drying exposure reducing the load bearing capacity for this type of beam.

The key point is that the climates chosen in the thesis (20°C/65% RH and 20°C/20-30% RH) are all equivalent to service class 1 according to EC5 (Eurocode 5 2004). A decrease in load-bearing capacity of the order of magnitude found (i.e. typically in the range of 15%) is of course not negligible and, therefore, there could be a need to introduce the effect of drying in design codes. A larger test program, to be used as a background for revisiting the k_{mod} factor of EC5, is thus of great interest.

Several observations of considerable interest were made on the basis of the numerical results in combination with the results from contact-free measurements. For multiple dowel-type joints loaded in tension parallel to the grain, a non-uniform strain distribution in the joint area was detected, see Paper VI. Shear strains and tensile strains, both parallel and perpendicular to the grain were found to be concentrated to the areas most likely to influence the failure mode of the joint. In tests of single dowel joints (Paper VII), both the contact free measurement system and the numerical analyses indicate the strain distribution around the dowel to be affected by the surface of the dowel. By comparing these experimental results with the numerical results, the coefficient of friction (μ) between the dowel and the surrounding timber was estimated. For joints with a smooth dowel surface μ was estimated to lie between 0 and 0.3. For joints with a rough dowel surface μ was estimated to lie between 0.3 and 0.5.

The experimental results of the joints reported in paper VII show that the load-bearing capacity increases when dowels with a rough surface are used as compared to using dowels with a smooth surface. In addition, the scatter of the test results (load-displacement curves) was seen to be much smaller for the case of using rough surface dowels. For the joints with a smooth dowel surface both the elastic response, as well as the plastic response varied considerably between different tests. These experimental observations confirm the advantages of using rough surface dowels as reported in previous studies. The equations given in EC5 do, however, not take into account these advantages.

The two numerical methods adopted in Paper VIII, see also Paper VII, in order to predict the capacity of multiple steel-timber dowel joints loaded parallel to the grain are very promising. For the first method, where fracture mechanics (LEFM) concepts were implemented, a good correlation to experimental results was seen. For example, the experimental mean load-bearing capacity for one group of joints was 313 kN. The corresponding calculated capacity was 312 kN. For the second method, where the single dowel capacity as given by EC5 was used as a failure criterion in the numerical simulations, a good correlation to traditional EC5 calculations of multiple dowel-type joints was obtained. For example, EC5 predicts a capacity of 195 kN for one group of joints. The corresponding capacity as calculated by the second numerical method was 198 kN. Both numerical methods were further capable to predict the different results for the two different joint types as seen in the experiments. Traditional EC5 calculations are not able to do so.

If comparing the experimental capacities presented in Paper VIII to the characteristic capacities as calculated using EC5, one can say that EC5 give results that for some configurations are too conservative. The fracture mechanics (LEFM) concepts adopted here is a possible workaround.

The second numerical method in Paper VIII is very promising if considering it as a complement to traditional EC5 calculations. One advantage of this method is that the method can be used to calculate the capacity of joints with the dowels placed in irregular patterns. Such joints cannot be analyzed using the formulae of EC5. From both a structural and an architectural point of view, this is of importance. Another advantage is that using this model it is straightforward to consider more complex loading situations, i.e. loads including eccentricities, which in turn give rise to moments. A larger parametric study in order to study different configurations is, however, needed before this method can be used by practicing engineers.

2.5.2 Thesis main conclusions

Thesis main conclusions are:

- The short-term capacity of multiple steel-timber dowel joints loaded parallel to the grain can be negatively affected by an initial drying exposure.

- An initial drying exposure can increase the brittleness of steel-timber dowel joints loaded parallel to the grain.
- The short-term capacity of inverted, double-tapered glulam beams can be negatively affected by an initial drying exposure.
- Moisture induced stresses are the explanation to the influence of moisture variations seen in the study. This was also the hypothesis of the thesis.
- The numerical methods presented in the thesis in order to predict the capacity of multiple dowel-type joints are very promising. Both methods are valuable tools and complements for a structural engineer.

Further conclusions:

- The experimental results of the multiple dowel-type joints tested in the thesis confirm the brittle failure tendencies for multiple dowel joints loaded in tension parallel to the grain, that have been reported in other studies.
- Use of contact-free measurements, when testing dowel-type joints, is a valuable complement to traditional experimental measurement techniques and also to numerical analyses.
- Increasing friction between the dowel and the surrounding timber increases the short-term capacity of single dowel-type joints loaded parallel to the grain.
- Increasing friction between the dowel and the surrounding timber gives less scattered test results.
- Inverted, double-tapered glulam beams are sensitive to defects at the inclined surface. Observations made during the experimental work indicated that the final failure usually was initiated in the area around knots.

2.5.3 Future work

The work presented in this thesis has shown that humidity changes can have a negative effect on the short term capacity of dowel-type joints. However, in the work performed, no solutions of how to best avoid this moisture influence have been presented. Thus, one interesting path to follow for future research efforts is the development of solutions to this problem. However, as discussed above, not only joints are negatively affected by moisture variations. Similar results were also seen for the beam-specimens tested in Paper V, which implies that further work should consider timber structures in general. A possible approach for future adoption to EC5, is to include the influence of moisture variations and gradients in the k_{mod} factor. Another method is to consider this type of moisture effects as an equivalent mechanical load. In Ranta-Maunus (2003) this method is suggested for timber structures.

For the capacity of multiple dowel-type joints – both with and without exposure of moisture variations and gradients – a larger experimental and numerical study of the effects of different joint configurations is of interest. In the thesis, attention was mainly directed to the spacing between the dowel rows perpendicular to the grain. The effect of changing other parameters as well as of adding loads at different angles, eccentricities and moments etc. to the joint have scarcely been dealt with in the literature. Using contact-free measurement methods together with numerical analyses is one way to increase the knowledge about the behavior of such joint.

The numerical methods proposed in paper VII and VIII are very promising. It would be of great interest to study those methods further.

Ductility aspects of dowel-type joints are another area which needs more focus. If using today's design equations it is very difficult to design large scale joints and assuring a ductile behavior. In principle, three different approaches are of interest here: a) using slender dowels, b) using local reinforcement of the joint area by the use of technical textiles, and, finally, c) assuring by geometrical design or possibly material choice the failure to take place in the slotted-in steel plates. In a master thesis (Clase and Nilsson 2006) this was tested with promising results.

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PART II:
APPENDED PAPERS