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Static and dynamic fatigue of finger joints

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Contents

Abstract

The results from a project on static and dynamic fatigue of finger jointed timber are reported. This project formed part of the research programme "Rammeprogram for Halm og Træ." The main part of the results were obtained as part of two diploma projects at Building Materials Laboratory, DTH.

A Finite Element Method calculation of different finger joint profiles has been performed. Significant stress concentration around the end of the finger tips is demonstrated.

The time to failure of finger jointed beams subjected to long term static load is found to be in good agreement with the values predicted by the well-known Madison curve. The life time of finger jointed timber under dynamic load is markedly shorter than for static long term load. Both static and dynamic long term load cause a larger proportion of glue failure compared to short term load.

1. Introduction

Finger jointing in glulam and structural timber is widely used as a method of obtaining large dimensions. The finger joint is normally the weaker part of the timber and therefore determinative in the design phase. Reduction of strength caused by the finger joint can be evaluated through laboratory tests of short term strength. The long term strength of finger joints is taken to be equal to the long term strength of non-jointed timber. The k_{mod} factor for solid wood of the EC5 code is thus taken to be valid also for finger jointed timber. However, no experimental evidence is available to substantiate this assumption; duration of load results are available only for timber without finger joints. It could be hypothesized that high stress concentration around the finger tips of a finger joint are what causes short term failure. If such stress concentration relax during long term loading the relative strength reduction thus would perhaps be less for finger jointed wood than for non-jointed wood. The present investigation is aimed at producing qualitative evidence to prove or disprove this hypothesis.

As part of the investigation a number of slow cycle fatigue tests were included. This served the purpose of producing qualitative evidence of whether or not finger joint strength is reduced more rapidly by cyclic loads of a frequency relevant for the design of wooden wind mill blades.

The strength and fatigue properties of finger jointed timber were examined promarily in two diploma projects carried out during 1991 and 1992 at the Building Materials Laboratory. In the first project (Nielsen 1991) existing literature on finger joints was initially reviewed and a collection of abstracts was produced. A series of tests concerning the short term strength and static and dynamic fatigue strength of finger jointed beams was performed.

In the second project (Mullit & Nielsen 1993) a Finite Element Method calculation was performed for different finger joint profiles. Tensile tests on finger jointed boards were performed and finally static and dynamic fatigue was examined and compared to the results obtained in the first project.

An evaluation of the strength loss factor k_{mod} for long term load assumed in the timber codes is carried out based on the two projects.

2. Background

2.1 Properties of finger joints

The main advantage of jointed wood is the possibility of obtaining structural timber in any desired length. Furthermore, the quality of the material can be improved by cutting away sections of weak timber and knots. The best way of gluing two pieces of wood is with a joint parallel to grain. The most simple end joint is the plain scarf joint (Fig.1).

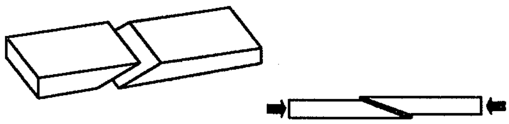

Fig.1 Plain scarf joint

This type of joint has a high tensile strength, but because of excessive waste when the profile is cut and poor stability during production the plain scarf joint is not much used in actual production. The finger joint was developed in order to obtain a self-adjusting joint with economical use of material and satisfactory mechanical properties. The production of strong and durable finger joints depends on a number of properties. A brief discussion of these factors will be presented in the following paragraphs, based on the literature review in (Nielsen 1991).

2.1.1 Geometry

The geometrical parameters of a finger joint are illustrated in Fig.2. The profile is defined by the four measures L, p, t_c and s. L denotes the length of the fingers and is used to name the profile (e.g. I-10, I-30). p is the width of the finger root, t_c the width of the finger tip and s the width of the gap at the end of the finger tip. According to DIN 68140 the gap is defined by $s \sim 0.03 \cdot L$. From these parameters the angle of the fingers α can be calculated.

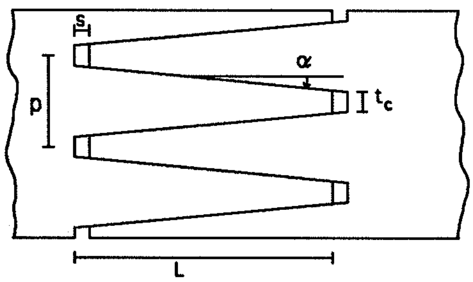

Fig.2 Finger joint geometry.

The dependence of these geometry parameters on the strength of joints has been subjected to numerous investigations. One of the main conclusions has been that it is important to minimize the width of the finger tip as this part of the joint does not contribute to the transformation of stresses through the cross-section. Incidently, the equipment used for cutting the profiles sets a lower limit to the width of the fingers. Moreover, some investigations suggest that the glued area has to be as large as possible, meaning that long fingers with flat slopes are beneficial. It has to be remembered though that very long fingers increase the amount of material wasted when the profile is cut.

2.1.2 Quality of timber

Through experiments it has been confirmed that the quality of timber is more critical to the strength of finger joints than the geometry of the profile. Failure is often initiated by knots, hence the British, German and European Standards for finger joints all include restrictions to the amount and size of knots in the vicinity of the joint. The relationship between density and strength of finger joints has been examined by a number of researchers. Even though density is normally regarded as a good indicator of strength this parameter does not accurately predict finger joint strength.

2.1.3 Gluing and hardening

The types of glue most frequently used for structural finger joints are resorcinol- and urea-melamineglues. The choice of glue depends on e.g. whether the joint is in timber for structural use, exposed to indoor or outdoor climate etc. Price, hardening time and colour are also to be considered.

After application of glue, the profiles are jointed under high pressure for about 1-2 min. Subsequently the finger joints have to harden, either at room temperature or at elevated temperatures. Preheating of profiles is often used as a method of speeding up the hardening process.

2.1.4 Failure in finger jointed timber

Failure in finger jointed timber can be divided in two main groups. Either the failure takes place in the finger joint or outside the joint. Finger joint failures can be caused by total separation of the glue joint or by rupture of the fingers at the finger root or by a combination of these two types. Failure outside the joint is normally caused by weak spots like knots or reaction wood.

2.2 Fatigue strength of wood

2.2.1 Static fatigue

It is a well-known fact that timber subjected to load loses strength during its life time. The relationship between long term strength and short term strength has been thoroughly investigated. In the ASTM standard from 1915 a long term strength of 9/16 ≈ 56% of the short term strength is suggested. This ratio has been used as a reference for comparison of various life time models.

A series of experiments carried out in 1947 on small specimens of clear wood resulted in a life time model referred to as the Madison curve. A linear semi-logarithmic relationship between stress level (SL) and life time was proposed:

$$SL = 90.4 - 6.3 \cdot \log t_f \qquad (t_f \textit{ in hours})$$

According to this expression the 9/16 stress level is reached after 30 years.

Experiments on structural timber with a moisture content of 11% and 20% (Hoffmeyer 1990) have led to the following life time models:

$$SL = 95.03 - 6.36 \cdot \log t_f \qquad (11\% \ m.c.)$$
$$SL = 84.52 - 5.11 \cdot \log t_f \qquad (20\% \ m.c.)$$

The moisture content of the wood in the experiments that are to be reported is 14%. For reasons of comparison a life time model for a moisture content of 14% can be calculated by interpolation of the Hoffmeyer models:

$$SL = 91.53 - 5.94 \cdot \log t_f \qquad (14\% \ m.c.)$$

The 9/16 stress level is reached after 99 years. The two models presented are illustrated in Fig.3.

Only one previous survey of static fatigue for finger joints has been found in the literature. No significant change of life time for finger jointed beams compared to normal structural timber was established.

2.2.2 Dynamic fatigue

The long term strength of timber subjected to pulsating load has not been given a great deal of attention, although some experiments have been performed. The durability at a given stress level can be expressed as either real time to failure, loaded time to failure or number of cycles to failure. The load frequency has been shown to be of great importance for the durability. At high frequencies the timber can endure a larger number of load cycles than at low frequencies. On the other hand the life time is longer at low load frequencies, and finally approaches the life time for static load. This is obviously due to the fact that the period without load at high frequencies is less than the relaxation time for wood whereas at low frequencies a certain relaxation of stresses can take place in the periods without load.

Dynamic fatigue for finger jointed tension specimens has been tested by Bohannan and Kanvik (1969). With a load frequency of 15 Hz the 9/16 stress level was reached already after about 2½ hours. As an example of the life time at lower frequencies a time to failure of about 9 days at a 74% stress level has been found for ordinary pine loaded with a frequency of 0.001 Hz.

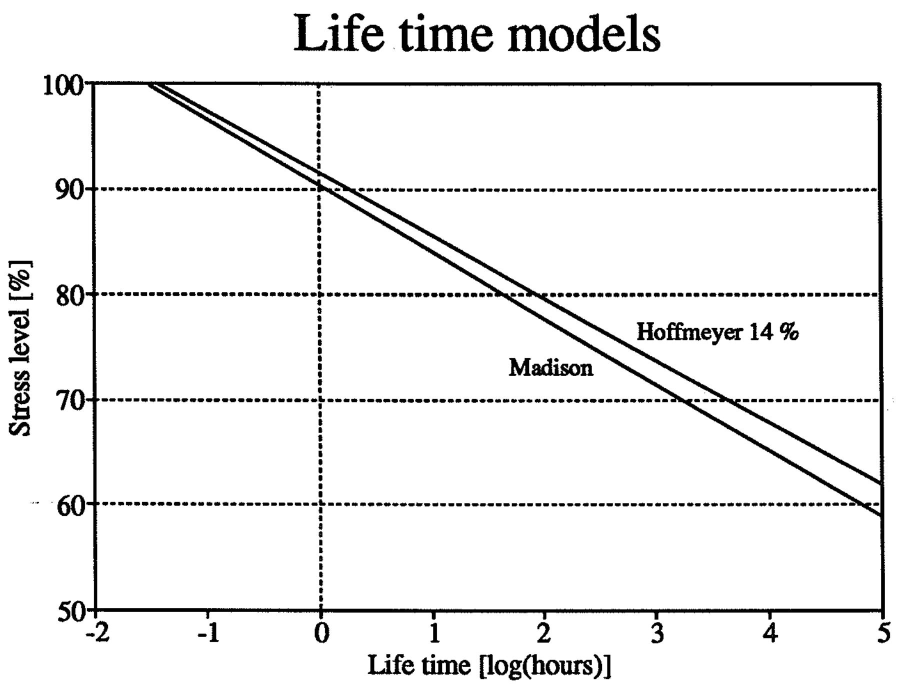

Fig.3 Life time models for clear wood (Madison) and structural timber with 14% moisture content (Hoffmeyer 14%).

3. Strength of finger joints by P. Nielsen.

The purpose of the experimental part of this project was to examine the strength properties of finger jointed timber and the dependency of density, moisture content, beam height, static and dynamic fatigue. Additionally, the use of acoustic emission measurements was examined as a means of predicting the strength of finger jointed timber.

3.1 Materials

A total of 250 beams was tested, 200 being high quality spruce beams (45 x 120 x 2000 mm), and 50 being HQL[1] spruce beams with dimensions 45 x 140 x 2000 mm. In order to test the effect of different beam heights 25 of the HQL beams were cut into two beams with dimensions 45 x 95 x 2000 mm and 45 x 45 x 2000 mm.

Before finger jointing all beams were matched, i.e., they were cross cut in the middle and paired with another beam. One end of beam no. 1 was then jointed with the opposite end of beam no. 2 and vice versa. This matching technique was introduced to create "identical" pairs of beams, and thereby get a better basis for evaluating the influence of density and moisture content independent of strength variations. Furthermore, the strength of beams to be tested for static or dynamic fatigue could be predicted more accurately, as the twin beam had already been tested.

The finger joints were made with L = 10 mm, p = 3.8 mm and t_c = 0.6 mm, i.e., corresponding to the German I-10 profile. The joints were glued with a resorcinol adhesive. All beams were conditioned at 75% RH to a moisture content of 14%, except for 25 beams that were conditioned at 90% RH to a moisture content of about 21%.

3.2 Methods

3.2.1 Short term bending strength, density and moisture content

A total of 225 finger jointed beams was tested for short term bending strength in an Instron 100 kN testing machine. The arrangement is shown in principle in Fig.4. The load was applied at a rate of 15 mm/min corresponding to failure within two minutes. Bending strength and type of failure were recorded.

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[1]HQL (High Quality Lumber) is a special glued laminated timber product. Large glulam panels are produced by edge gluing tapered planks produced from small logs. Beams are then sawn from such panels.

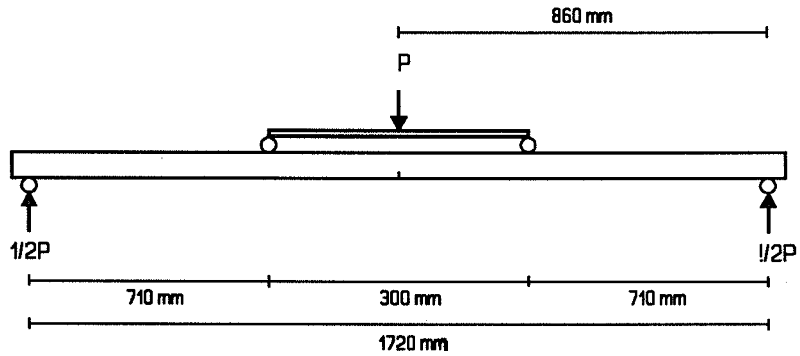

Fig.4 Load arrangement for bending tests.

Immediately after failure had occurred, two 13 mm discs were cut out on each side of the finger joint in a large number of the beams. The discs were weighed, dried at 103 °C for 48 hours, weighed again and finally weighed under water after impregnation with paraffin. Density and moisture content were then calculated.

3.2.2 Acoustic Emission

Twenty-five of the beams for short term strength testing were simultaneously tested with an equipment that measured the acoustic emission created during the load period. A sensor was placed at the face of the beam subjected to compressive stresses, and the number of counts during the period until failure was recorded.

3.2.3 Static fatigue

Twenty-five finger jointed beams were tested for static long term strength. The configuration of the load application onto the beam equaled the configuration used for testing of short term strength. The load consisting of steel in a barrel was transferred to bending of the beam via a pulley and wires as shown in Fig.5. The beams were loaded to 80% of the short term strength of the corresponding "twin" beam. When failure occurred, a timer registered the elapsed time, and type of failure was recorded.

3.2.4 Dynamic fatigue

Twenty-five finger jointed beams were tested for dynamic long term strength. The configuration was the same as described for static load with the addition of a pneumatic cylinder equipment capable of lifting the barrel at fixed intervals and thereby removing the load from the beam. Twelve beams were tested with a pulse period of 15 seconds (0.067 Hz) and 13 beams were tested with a pulse period of 125 seconds (0.008 Hz). Elapsed time until failure and type of failure were recorded.

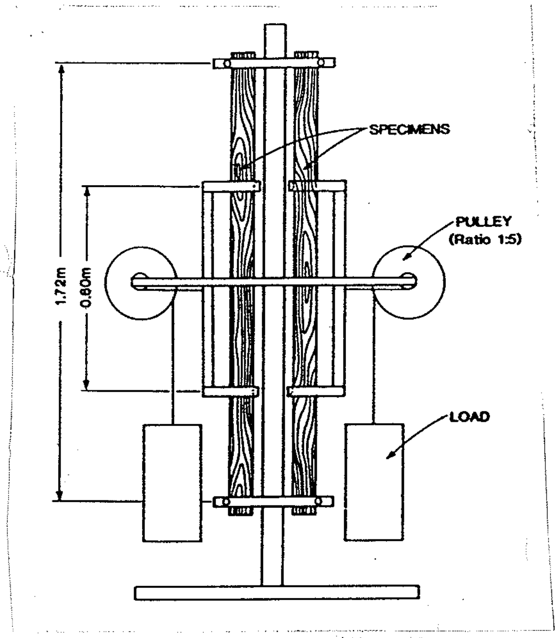

Fig.5 Equipment for long term testing.

3.3 Results

3.3.1 Short term strength tests

Type of failure: A total of 175 ordinary spruce beams was tested for short term bending strength. 79% of the beams broke due to failure in the finger joints. 30% of the finger joint failures were caused by separation of the glue joint, 53% by rupture of the fingers and 17% by a combination of these two types. 21% of the beams had failure outside the finger joint, 43% of these were caused by knots in the tension side of the beam and 57% were caused by failure in clear wood.

Matching: As a test of the quality of the matching technique 25 pairs of beams were loaded in bending until failure. Failure in the finger joints for both beams of the pair occurred in 15 cases. In Fig.6 the bending strength of these 15 pairs is shown. The standard deviation of the bending strength for the no.1 beams is 5.51 and for the no.2 beams 5.05. These values can be taken as an estimate of the quality of a prediction of strength based on the average value for one group of beams. The tests show that the strength of a beam can be predicted about twice as well, when the strength of a matching beam is already known, as the standard error of estimate for the regression line in Fig.6 is only 2.40. Consequently, the matching technique used in this project offers a good opportunity of a better prediction of strength.

Moisture content: The influence of moisture content on bending strength was examined for 25 pairs of beams, where one of the beams had been conditioned to a moisture content of about 14% and the other to a moisture content of about 21%. The average bending strength for the first group of beams was 48 MPa and for the second group it was 38 MPa. Consequently, the decrease in strength

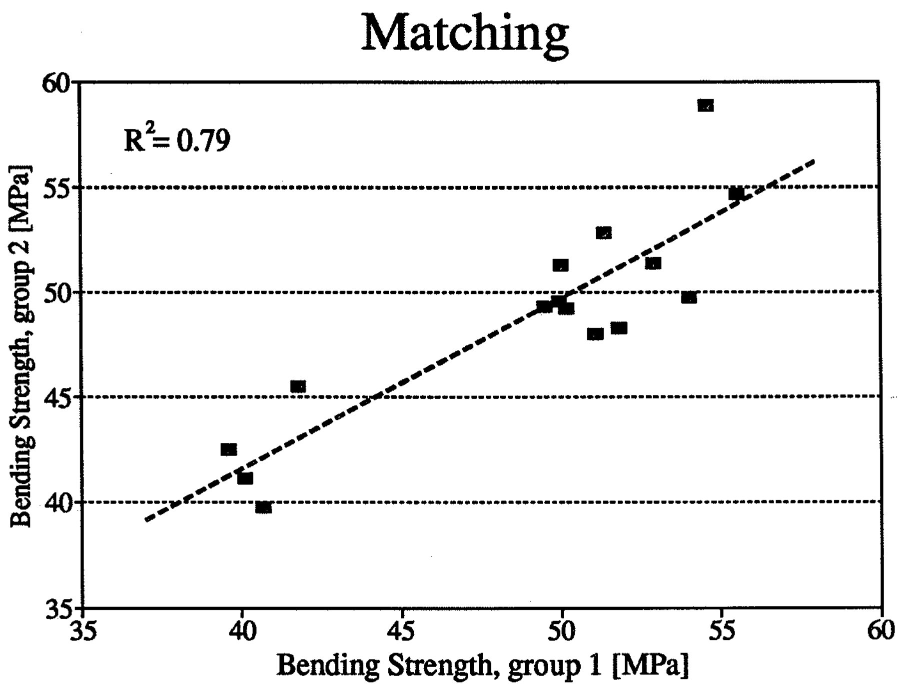

Fig.6 Bending strength of two groups of matched beams.

for a moisture content increase of 7% was about 21%. This is in good agreement with what has been found for structural timber without finger joints. No correlation between moisture content and type of failure was recorded. Both groups of beams had 76% finger joint failure.

Density: The density was found for all beams tested for short term strength. Fig.7 shows the relationship between bending strength and the average density of two discs taken from the beam on each side of the finger joint. There is a relatively poor correlation between strength and density. A part of the explanation could be that failure occurring in the glue joints or caused by knots (about 46%) cannot be expected to be related to the density of the beam.

Beam height: The effect of variation in beam height was tested for 75 HQL beams. Beam heights of 140 mm, 95 mm and 45 mm with 25 beams of each dimension were tested. The results are illustrated in Fig.8. It is evident that a lower beam height results in an increased bending strength. This is due to the fact that the probability of weak spots where failure can be initiated is greater for a larger dimension. The failure types for the HQL beams reflected the good quality of the timber. 88% were finger joint failures and 74% of these were caused by partial or full separation of the glue joint. Hence the amount of wood failure is substantially lower than for the ordinary spruce beams.

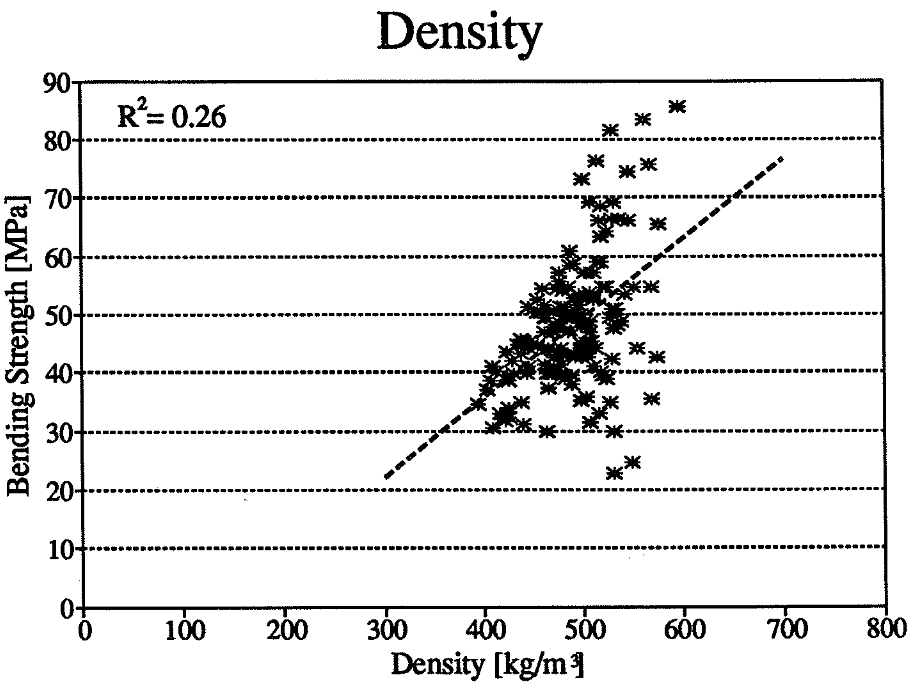

Fig.7 Bending strength vs. density for 175 beams.

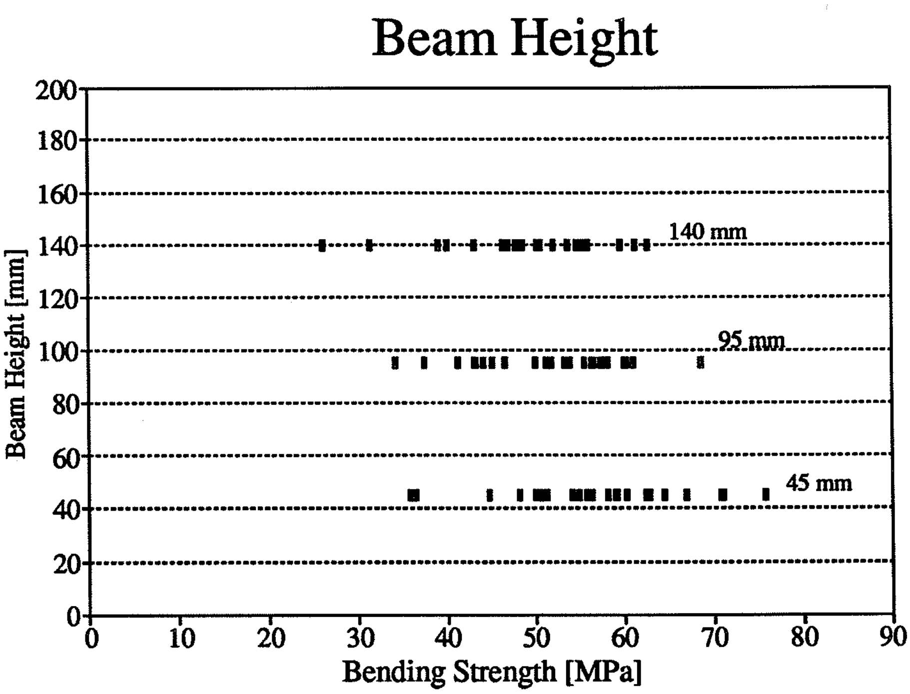

Fig.8 Bending strength vs. beam height for HQL beams.

3.3.2 Acoustic Emission

The experiments showed a poor correlation between accumulated counts and bending strength for the tested beams. An example of this relationship is shown in Fig.9. Apparently a threshold value indicating approaching failure cannot be established.

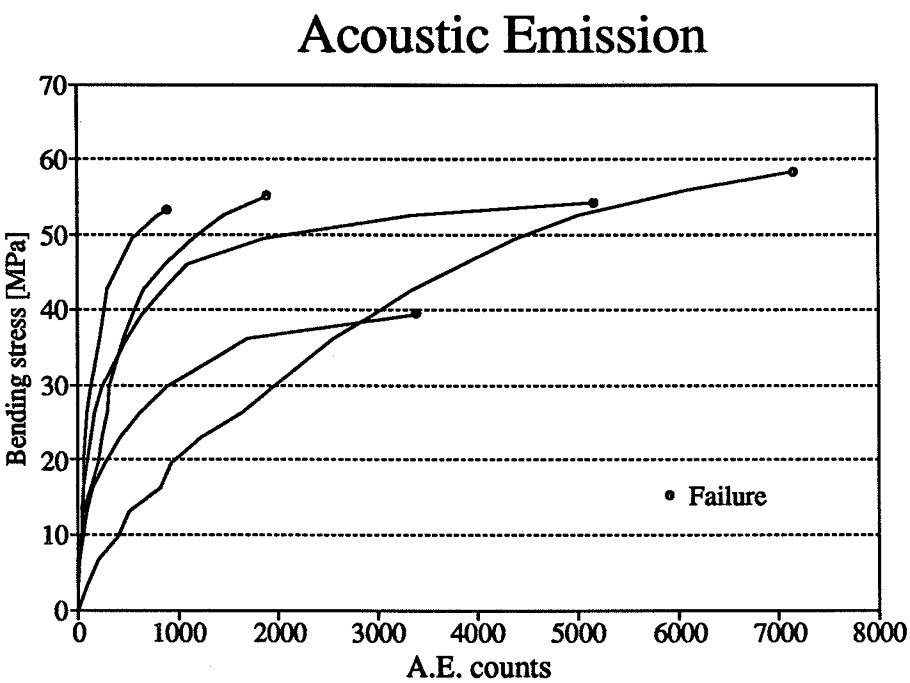

Fig.9 Acoustic emission counts during load for five selected beams.

3.3.3 Static fatigue

Static long term bending strength was tested for 25 beams loaded to a stress level of 80% of the short term bending strength of the corresponding twin beam. The results are presented in Fig.10 showing the relationship between bending strength and the elapsed time to failure for the 15 beams where failure occurred in the finger joints for both beams of the pair. The prediction of strength based on the result from the matching twin beam seems to be rather good, as there is just a weak tendency of early failure for strong beams. In Fig.11 the results are presented as a relationship between stress level and logarithm of time to failure. The best logarithmic fit for life time at the different stress levels is also shown in the figure. At a stress level of 100% the time to failure is 1.2 min (short term test). The life time at a stress level of 80% is estimated by calculating the average time to failure omitting both the first four and last four observations. Thereby the results are not affected by the

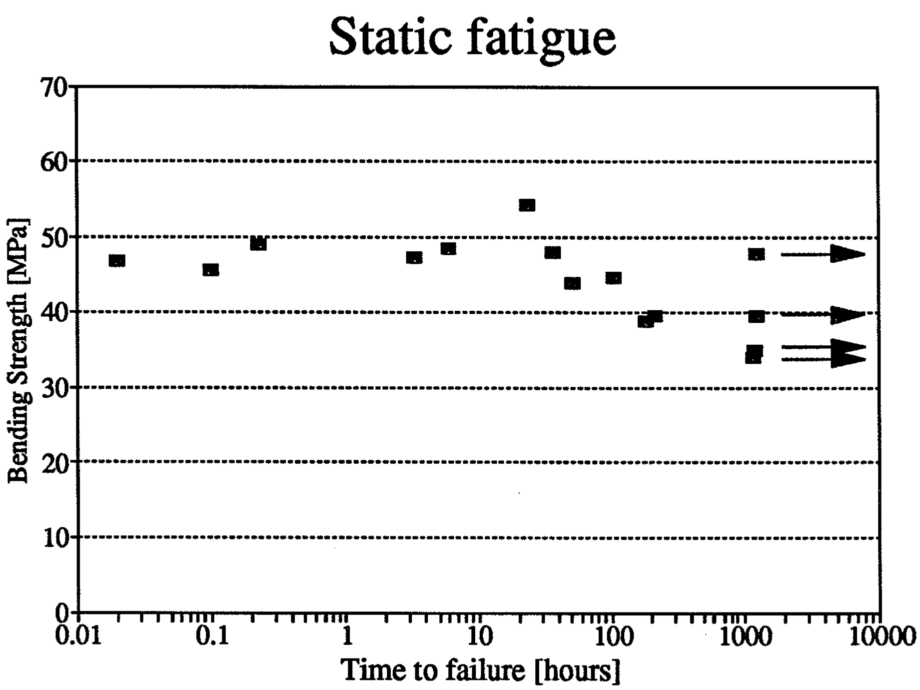

Fig.10 Life time for 15 beams with finger joint failure.

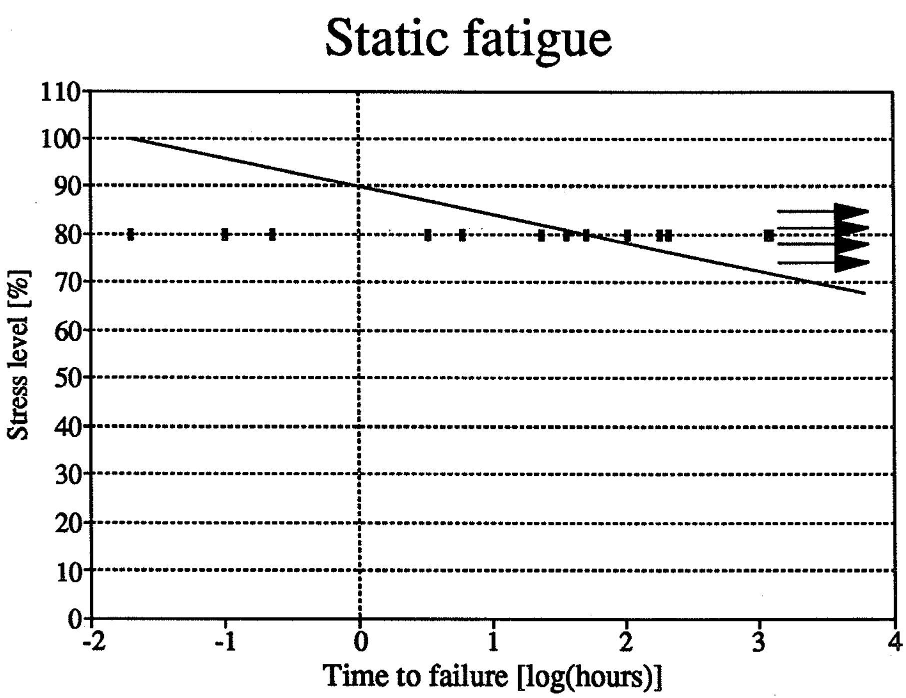

Fig.11 Life time model predicted by the results.

four beams that had not yet failed at the conclusion of the tests. An average life time of 51 hours at the stress level of 80% is found and the results can be described as:

$$SL = 90.02 - 5.87 \cdot \log t_f$$

The 9/16 stress level is reached after about 65 years. Judged by these tests the static fatigue for finger jointed wood is not as severe as for clear wood predicted after the Madison curves according to which this stress level should be reached in 30 years. On the other hand the results for structural timber previously referred to, suggest a period of 144 years before the 9/16 stress level is reached.

The 25 beams had 72% finger joint failure, 46% of these being failure in the glue joints, 31% rupture in the fingers and 23% a combination of these two types. Compared to the failure types for the short term strength test the amount of glue failure is somewhat higher.

3.3.4 Dynamic fatigue

Dynamic long term bending strength was tested for 12 beams with a frequency of 0.067 Hz and 13 beams with a frequency of 0.008 Hz. The stress level was also here 80% of the short term bending strength of the twin beam. Results for the 7 and 9 beams with finger joint failure are shown in Fig.12. The time scale displayed is real time, i.e., the beams are only under load for approximately half of this time.

When these results are compared to the results for static fatigue in Fig.10, it is evident that failure occurs considerably earlier when the beams are subjected to dynamic load. In Fig.13 the results are shown together with the logarithmic fits for the relationships between life time and stress level:

$$SL = 84.38 - 9.36 \cdot \log t_f \qquad (0.067\ Hz)$$
$$SL = 83.17 - 10.08 \cdot \log t_f \qquad (0.008\ Hz)$$

The 9/16 stress level is reached after 42 days and 20 days respectively. These results contradict what could be expected, namely a longer time to failure at low frequencies. This result is not to be overemphasized as the number of observations is limited and the actual difference between the two frequencies is very little considering the variation.

The 25 beams had 60% finger joint failure, 73% of these being failure in the glue joints and 27% rupture in the fingers. Hence glue failure was about as frequent as for the static long term test.

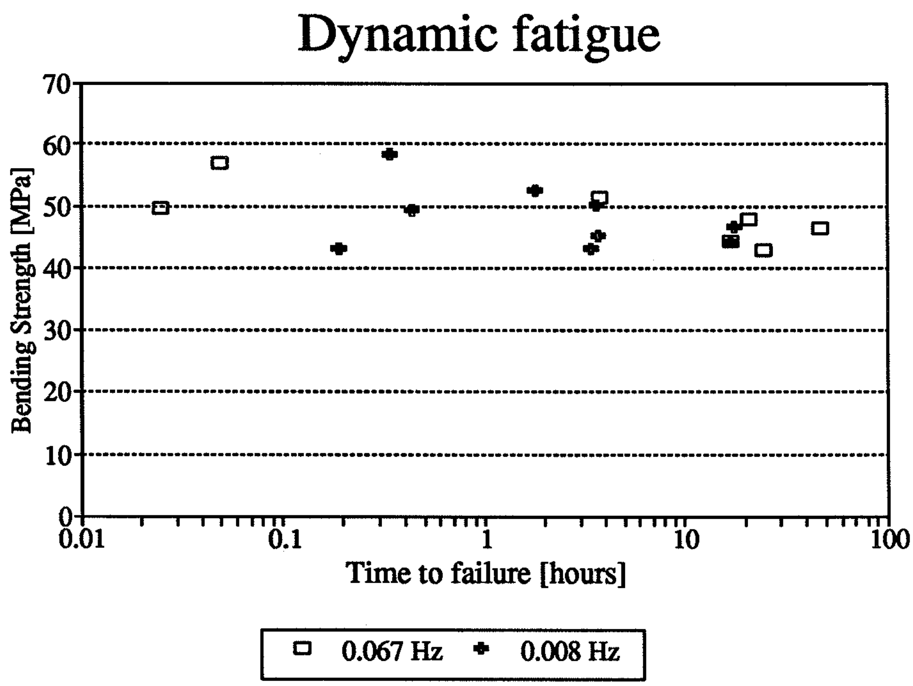

Fig.12 Life times for beams with finger joint failure.

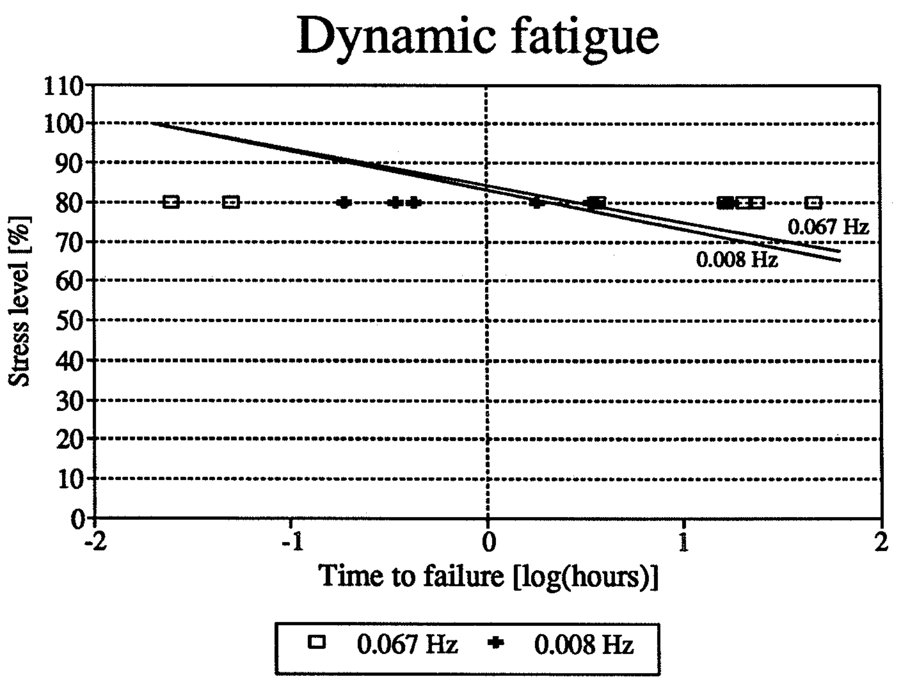

Fig.13 Life time models predicted by dynamic tests.

4. Fatigue strength of finger joints by P.M. Mullit & C.K. Nielsen.

In this project the Finite Element Method (FEM) is employed to study a model of finger joints subjected to tension parallel to grain. A verification of results from the FEM-simulations is attempted through tensile tests on boards with four different finger joint profiles. Furthermore static and dynamic fatigue are tested on another wood material and with a partly new equipment compared to the tests carried out by P. Nielsen summarized in the previous paragraph.

4.1 Finite Element Method modelling of finger joints

The Finite Element Method is a very useful tool for numeric calculations of in homogeneous structures with irregular constraints, which cannot be calculated analytically. A critical point in the calculation of a finger joint is modelling of the glue joint, as this is a very thin layer with properties differing considerably from the properties of the surrounding wood. Another thing which has to be considered is the potential of singular points, i.e., points where the calculated stresses theoretically are infinite. Consequently, the calculation of valid and useful results depends on an appropriate choice of the element mesh. This is particularly important around the finger tips, where other researchers have established a significant stress concentration.

4.1.1 Modelling

An FEM program called LUSAS was used in the present project. The calculations were made on a model of two halved fingers as illustrated in Fig.14, where the chosen element mesh can also be seen. The model was placed in an x-y coordinate system with the x-axis parallel to grain. An enlarged section of the mesh near the finger tip is shown on Fig.15. The mesh has been designed with 962 quadrilateral elements. The smallest elements are situated around the glue joint and finger tip where the stresses are expected to be at their maximum. All element measures are determined relative to the characteristic measures L, p, s and t_c for the finger joint as defined in Fig.2. This makes the calculation of different profiles far easier. The model was loaded with a uniform tensile stress $\sigma_{x,p}$ acting in the distance $L/4$ from the finger gap. All calculations were made with $\sigma_{x,p}$ = 1 MPa.

In the calculations wood was regarded as a linear elastic orthotropic material with the Young-moduli E_x = 11000 MPa and E_y = 300 MPa, shear modulus G = 500 MPa and Poisson ratio ν_{xy} = 0.01. The glue joint was regarded as a linear elastic isotropic material with Young's modulus E = 3600 MPa and Poisson ratio ν = 0.4.

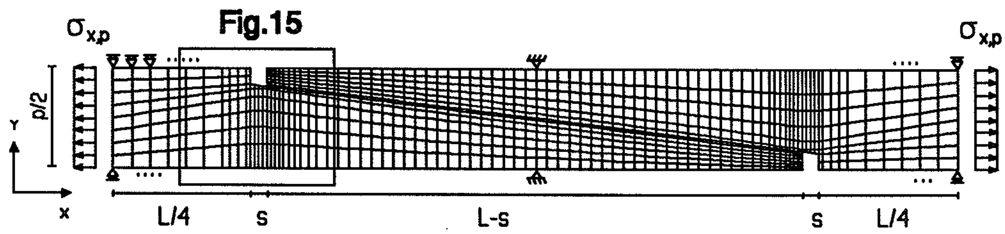

Fig.14 Total FEM-model.

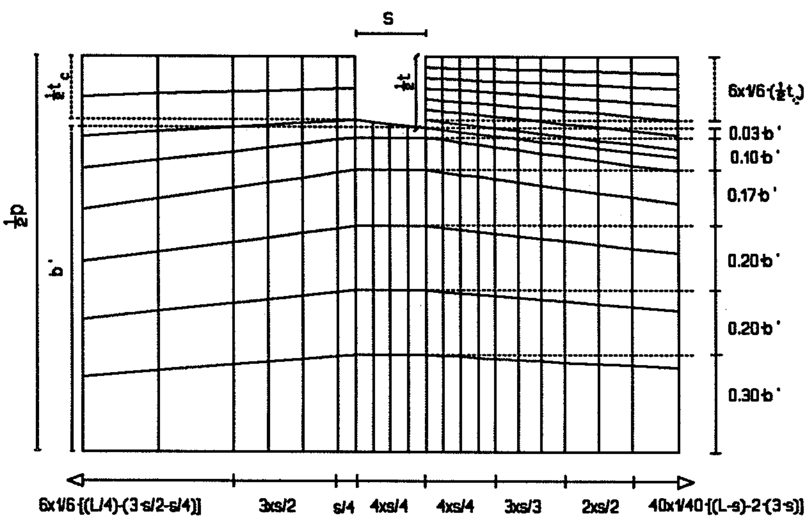

Fig.15 Enlargement of element mesh around finger tip.

4.1.2 Results

A full calculation was made for the German I-20 finger joint profile. The stresses were found in an *s,n* coordinate system with the *s*-axis parallel to the glue joint. This coordinate system was rotated the angle α (finger angle) with respect to the x-y system.

In Fig.16 the calculated stresses for the whole profile are illustrated. The normal stress parallel to the direction of the glue joint σ_s is shown with a contour value of 0.10 MPa, the normal stress perpendicular to the direction of the glue joint σ_n and the shear stress τ_{ns} with a contour value of 0.01 MPa. Evidently there is a solid concentration of stresses around the finger tip.

Some selected results for specific parts of the profile will be presented. The normal stress σ_s for the area around the finger tip and end of the glue joint is shown in Fig.17. The maximum stress concentration factor is 4.10 in the wood and 1.45 in the glue. The calculations show that the normal stress in the wood decreases to app. 1 MPa ($=\sigma_{x,p}$) after 20% of the glue joint length. The normal stress in the glue decreases rapidly to a minimum value of 0.30 MPa.

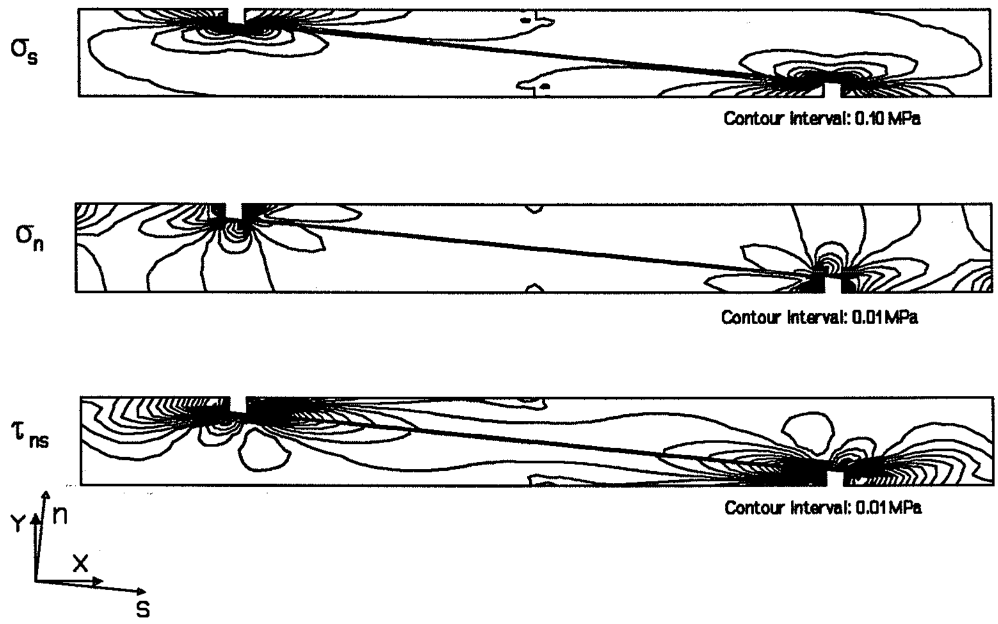

Fig.16 Calculated stresses for the total model.

It has to be mentioned that the magnitude of the maximum stresses is affected by the existence of a singular point at the corner of the finger tip. If a finer element mesh is used the calculated maximum stresses will move towards infinity. This means that the actual values are not necessarily true, yet they form a good basis for comparison of profiles.

The normal stress σ_x through a cut across the root of the finger is illustrated in Fig.18. A constant value of 1 MPa is reached after about 50% of the cut length corresponding to one fourth of the finger root.

The calculated shear stresses τ_{ns} around the finger tip are shown in Fig.19. The maximum shear stresses are 0.42 MPa in the wood and 1.06 in the glue. The shear stresses along the glue joint can be seen on Fig.20. A constant shear value of 0.12 MPa in both wood and glue is the result for the mid-half of the glue joint.

The normal stresses σ_n perpendicular to the direction of the glue joint are negligible compared to the values for σ_n and τ_{ns} just presented.

The FEM program enables a calculation of the resultant stress from von Mise's condition of yield. The resultant wood stresses are very similar to the normal stresses σ_s as this is the dominant stress type for the actual load. The resultant glue stresses are found to be a combination of normal stress σ_s and shear stress τ_{ns}.

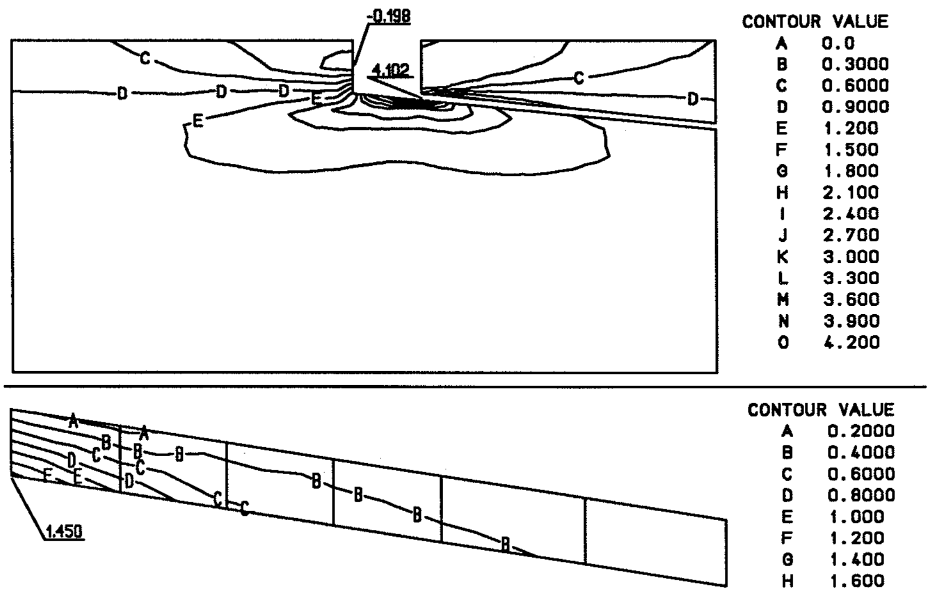

Fig.17 Calculated normal stresses σ_s in the wood around the finger tip and in the glue at the end of the glue joint.

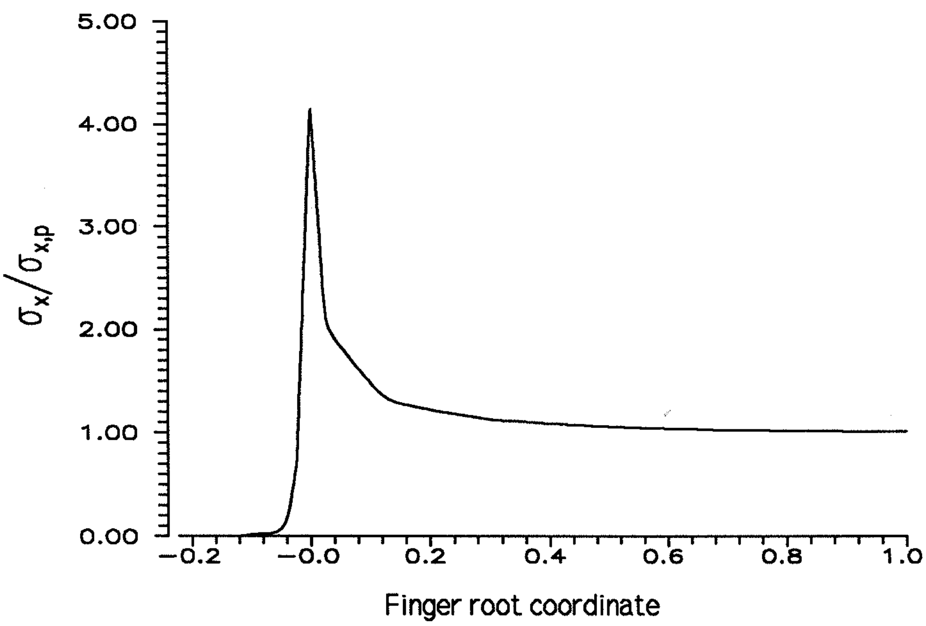

Fig.18 Normal stresses in the finger root.

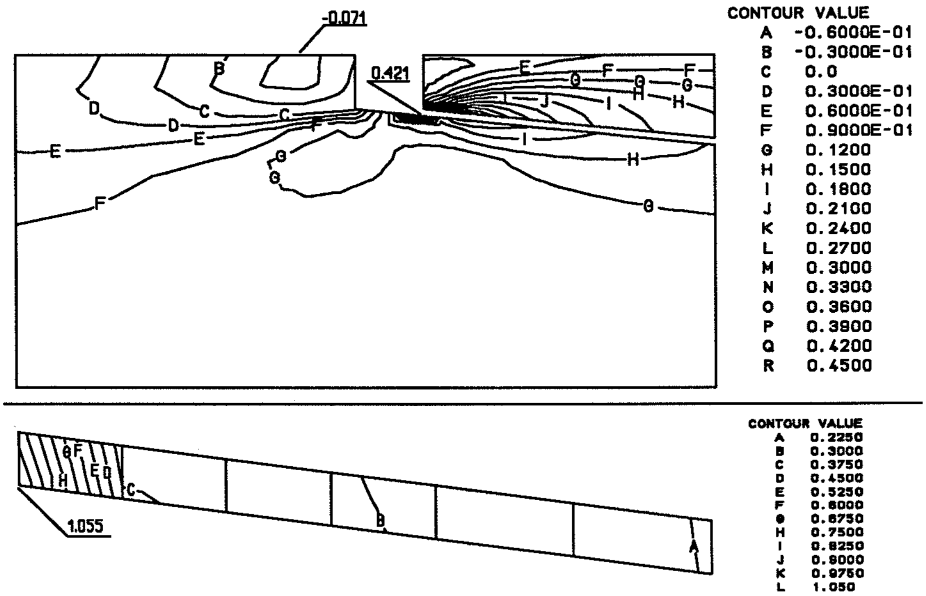

Fig.19 Calculated shear stresses at the end of the finger tip.

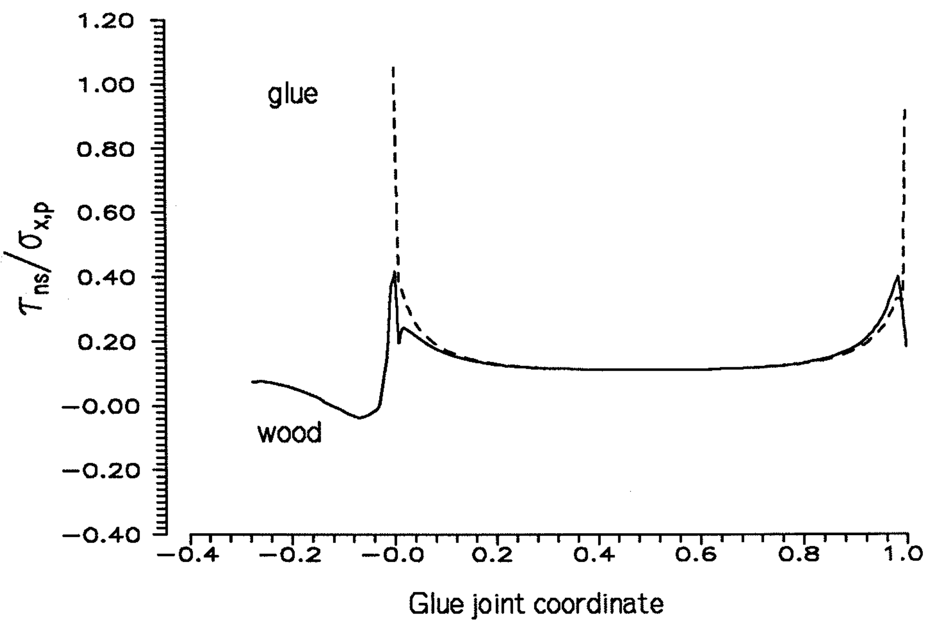

Fig.20 Shear stresses in the wood and glue along the glue joint.

According to the calculations failure in a finger joint will initiate at the finger tip and propagate either along the glue joint due to high shear stress or through the root of the finger due to high normal stress. This is illustrated in Fig.21.

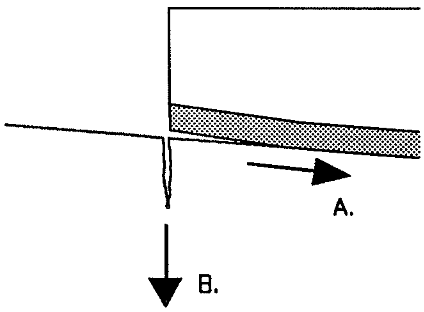

Fig.21 Failure initiating along the glue joint (A) or across the finger root (B).

The effect of a different finger tip geometry was examined by running a series of calculations where the corners of the finger tip were rounded, i.e., the width of the glue joint gradually increased towards the end. This resulted in somewhat lower stress concentrations in the end of the glue joint whereas the stresses in the wood were almost not affected.

A comparison of different finger joint profiles was performed. Calculated shear stresses in the glue τ_{ns} in four selected profiles are shown in Fig.22. The maximum stress concentration was found in the I-10 profile closely followed by the I-20 profile. The stress concentration in the I-40 and I-30 profiles with longer fingers were considerably lower.

Based on the geometrical characteristics of the profiles a classification of predicted strength was attempted. A low finger tip/finger root ratio was assumed to be beneficial to the strength. Additionally a high relative glue area and high finger gap (*s*) - finger tip ratio was preferred. Taking these three relative measures into account the I-30 profile was expected to cause minimum stress concentration, followed by I-40, I-20 and finally I-10. This ranking is similar to what has been found from the FEM analysis.

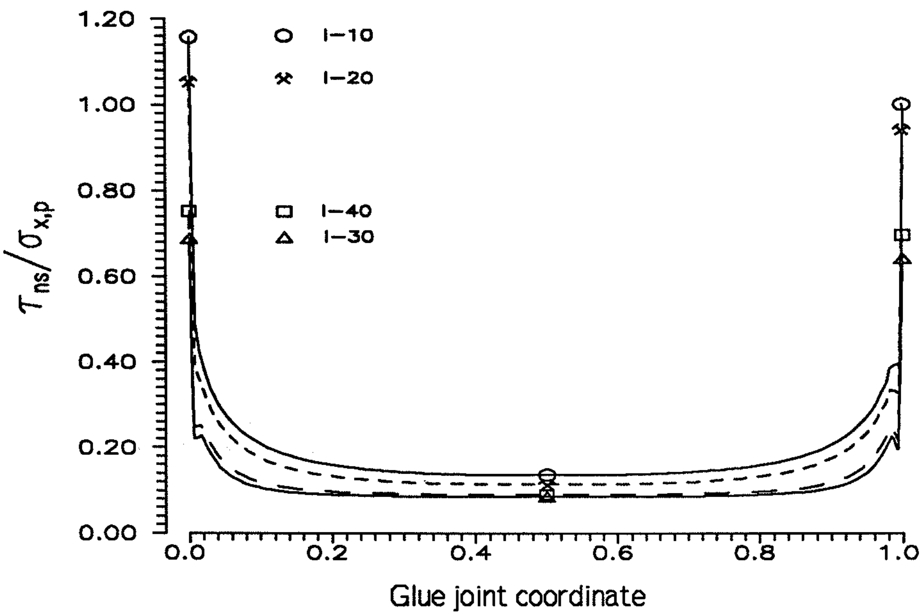

Fig.22 Shear stresses along the glue joint for four different finger joint profiles.

4.2 Experimental verification of FEM results

In order to evaluate the results from the FEM simulations a series of tensile tests with four different finger joint profiles was carried out.

4.2.1 Materials and methods

A good quality of timber was chosen for the tests as it was failure in the finger joints that were of interest. Specially selected spruce boards with the dimension 37 x 85 mm were obtained. Before finger jointing the boards were matched in a manner similar to the matching of beams in the previous project. The I-20 finger joint profile was used as a reference, i.e., one of the boards in the pair was made with this profile and the other with either I-20 (10 pairs), I-10 (20 pairs), I-40 (20 pairs) or a modified version of I-20 with rounded fingers (20 pairs). A resorcinol adhesive was used for the finger joints. The boards were split and planed to a final test specimen dimension of 10 x 72.6 x 1200 mm.

The tensile tests were performed in a 500 kN AMSLER test machine. The load was applied at a rate which led to failure within two minutes. The tensile strength and type of failure were recorded. Specific gravity and moisture content were determined for 12 randomly chosen specimens.

4.2.2 Results

A total of 140 finger jointed boards was tested. 87% had failure in the finger joints, 66% of these were caused by failure in the glue joint, 3% were caused by rupture of the fingers and 31% were a combination of these two types. 13% of the boards had failure outside the finger joint caused by knots or simply failure in clear wood. Normally the type of failure was the same for the two boards in the matched pairs. Consequently, the type of failure was not related to the type of profile.

Average values of density and moisture content of randomly chosen specimens were 470 kg/m^3 and 11% respectively.

Results for the four types of profiles are shown in Fig.23 - 26. The relationship between tensile strength of the profile and strength of the I-20 reference profile is illustrated. *Only results where both boards of the pair had finger joint failure are included.* A statistical analysis has been carried out to test the validity of the results.

The matching of profiles can be judged by Fig.23. The standard deviation of the strength not considering the matching was 12.5 MPa whereas the standard error of estimate for the regression line was 3.77 MPa. Evidently the matching has been successful.

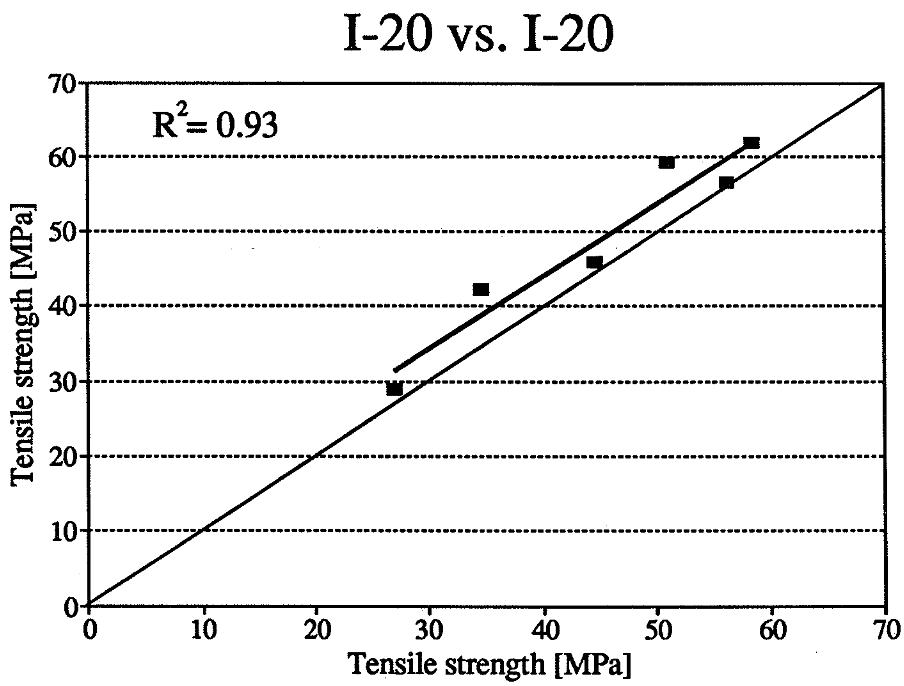

Fig.23 Matching of I-20 profiles.

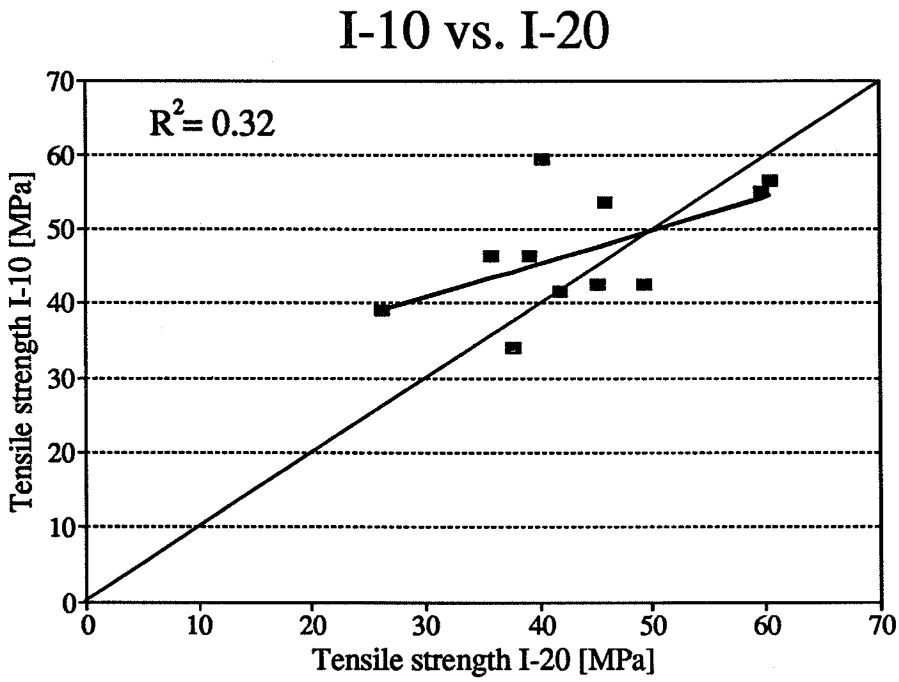

Fig.24 Tensile strength of I-10 profiles vs. I-20.

The I-10 profile (Fig.24) has an average strength that is 7% better than I-20. It has to be noted though that the statistical value of the regression line is dubious (R^2 = 0.32), even though the two averages are found to differ on a 95% significance level.

The average strength value of the I-40 profiles (Fig.25) was only 72% of the values obtained for the I-20 twin boards. Even though the regression line is very poorly determined (R^2 = 0.07) and the analysis showed that the two averages did not differ on a 95% significance level, it can be concluded that the I-40 profile is weaker as only two out of seventeen results contradict this hypothesis.

Rounded finger tips seem to lead to increased strength of the finger joint profile. The average tensile strength of the modified I-20 profile (Fig.26) is 12% greater than for the normal I-20 profile.

Owing to difficulties when the profiles were cut the actual geometries of the tested profiles were a bit different from what is prescribed in the standards. This was particularly the case for the I-40 profile. A direct comparison of results from the tensile tests with results from the performed FEM analysis is therefore not possible.

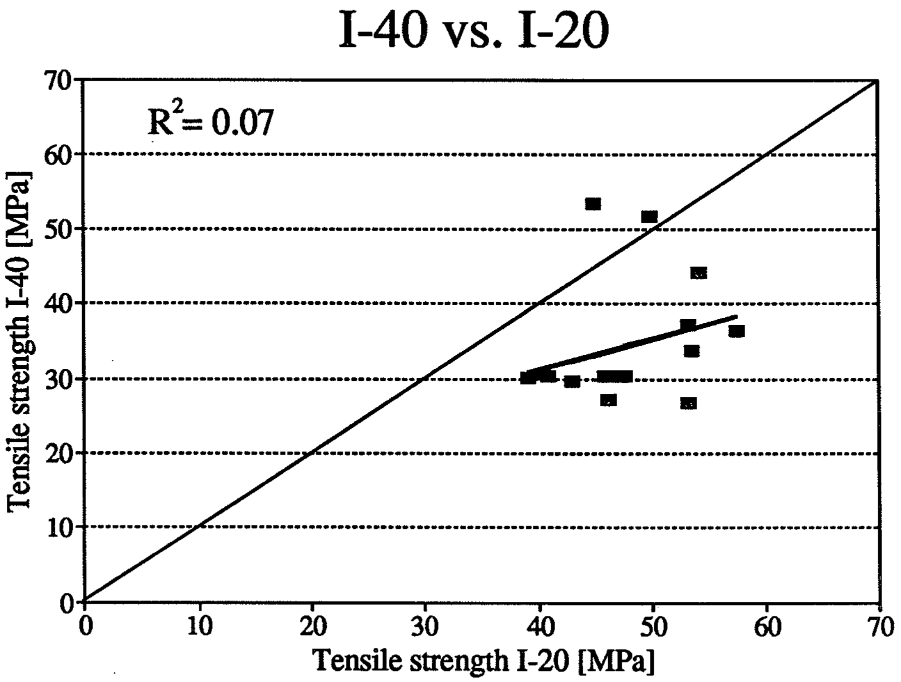

Fig.25 Tensile strength for the I-40 profile vs. I-20.

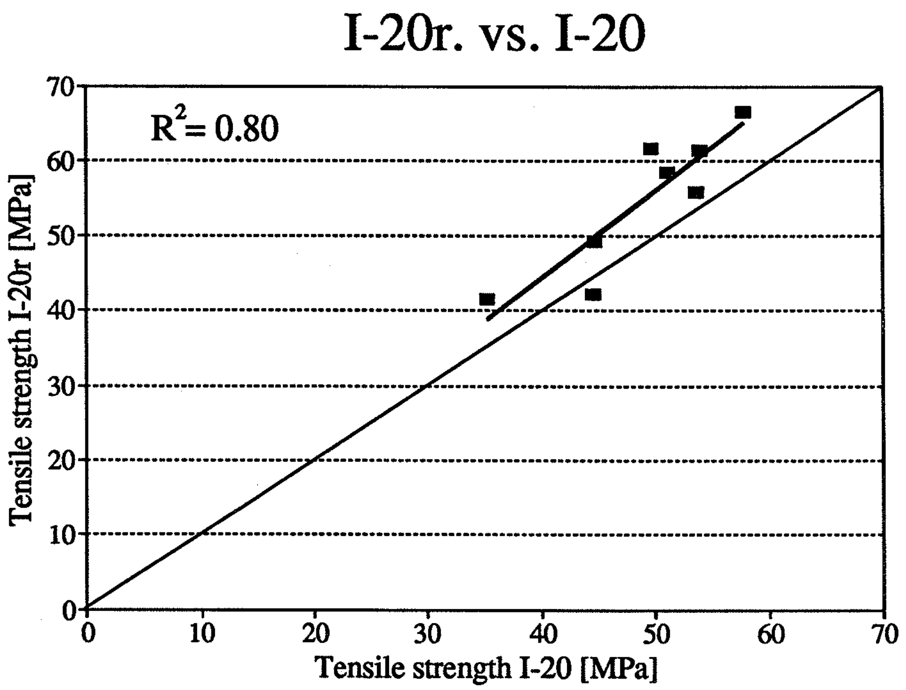

Fig.26 Tensile strength of the I-20 profile with rounded fingers vs. normal I-20.

A new FEM calculation with the actual profile geometries was attempted. The results were somewhat ambiguous as an estimation of profile strength would depend on what type of stress (glue or wood, normal or shear) that was estimated to be critical. A ranking of the profiles as proposed in section 4.1.2. could not be established.

A comparison of the results from the new FEM calculation and the tensile tests enabled an evaluation of the severeness of different stress types. The increased strength found in the tensile tests of the I-10 and the modified I-20 profile compared to the normal I-20 was apparently caused by lower normal and shear stresses in the glue joint. The decreased strength of the I-40 profile was caused by higher normal stresses in the wood near the finger root.

4.3 Bending and static and dynamic fatigue tests

4.3.1 Materials and methods

Glulam spruce beams with five lamellae glued with resorcinol adhesive were tested for bending strength. The outermost tension lamella contained a finger joint with a melamine-urea-formaldehyde glue. Beams of 100 x 200 x 2000 mm were split and planed, thereby creating 37 pairs of matched twin beams with dimensions 45 x 95 x 2000 mm. The beams were conditioned at a relative humidity of 75%.

Short term bending strength and static Young's modulus were found in the Instron testing machine also used in the experiments carried out by P. Nielsen. Young's modulus was determined for all 74 beams whereas 37 beams (one in each pair) were loaded until short term failure.

The stress levels chosen in the fatigue tests were 75% of the short term strength for static load and 70% for dynamic load. The equipment and load configuration for the static fatigue test was the same as used by P. Nielsen. In the dynamic fatigue test 10 beams were tested at a frequency of $1.85 \cdot 10^{-5}$ Hz using the same equipment as P. Nielsen (load barrels lifted by pneumatic cylinders). Ten other beams were tested with a frequency of 0.05 Hz using a new equipment where the beams were loaded directly by a pneumatic cylinder controlled by a computer.

After failure had occurred, the type of failure was recorded and specimens were taken from all the beams in order to determine density and moisture content.

4.3.2 Results

Type of failure: The 37 beams tested for short term strength had 95% finger joint failure. 28% of these were caused by failure in the glue joint, 37% by rupture of the fingers and 35% were a combination of these two types. The 17 beams tested for static fatigue had 92% finger joint failure, 63% of these being glue joint failure, 28% rupture of fingers and 9% a combination. The 20 beams tested for dynamic fatigue had 89% finger joint failure, 40% of these being glue joint failure, 31% rupture of fingers and 29% a combination. No significant dependence of frequency was detected.

Obviously the risk of glue failure is greater for beams subjected to long term loading, especially static load. This may be caused by a redistribution of stresses in the finger joint or weakening of the glue.

Density and moisture content: The relationships between density and bending strength, density and Young's modulus, moisture content and bending strength and finally moisture content and Young's modulus were all examined. In all cases the correlation was poor with R^2-values ranging from 0.00 to 0.11.

Young's modulus: The determination of Young's modulus did not produce satisfactory results. No correlation was found between Young's modulus of twin beams and likewise the relationship between Young's modulus and bending strength was uncertain. Owing to problems with the measuring equipment, it was concluded that the results were useless.

Static fatigue: Results for beams with finger joint failure are shown in Fig.27. Three beams had yet to fail at the conclusion of the experiments. In Fig.28 the results are shown together with a logarithmic fit for the relationship between stress level and time to failure.
A life time of 2 min at 100% has been assumed. At a stress level of 75% the logarithmic mean of the mid-three observations was used.

$$SL = 90.21 - 6.62 \cdot \log t_f$$

The 9/16 stress level is reached after 15 years. These results indicate a reduced durability compared to both the Madison curves and the results obtained by P. Nielsen.

Dynamic fatigue: Dynamic long term bending results for beams with finger joint failure are shown in Fig.29. In Fig.30 the life times at a 70% stress level are illustrated. With average life times calculated similar to the results for static fatigue the logarithmic fits can be described as:

$$SL = 88.90 - 7.51 \cdot \log t_f \qquad (1.85 \cdot 10^{-5}\ Hz)$$
$$SL = 84.60 - 10.42 \cdot \log t_f \qquad (0.05\ Hz)$$

The 9/16 stress level is reached after 928 days and 22 days respectively, i.e., according to these experiments a lower frequency results in prolonged time to failure.

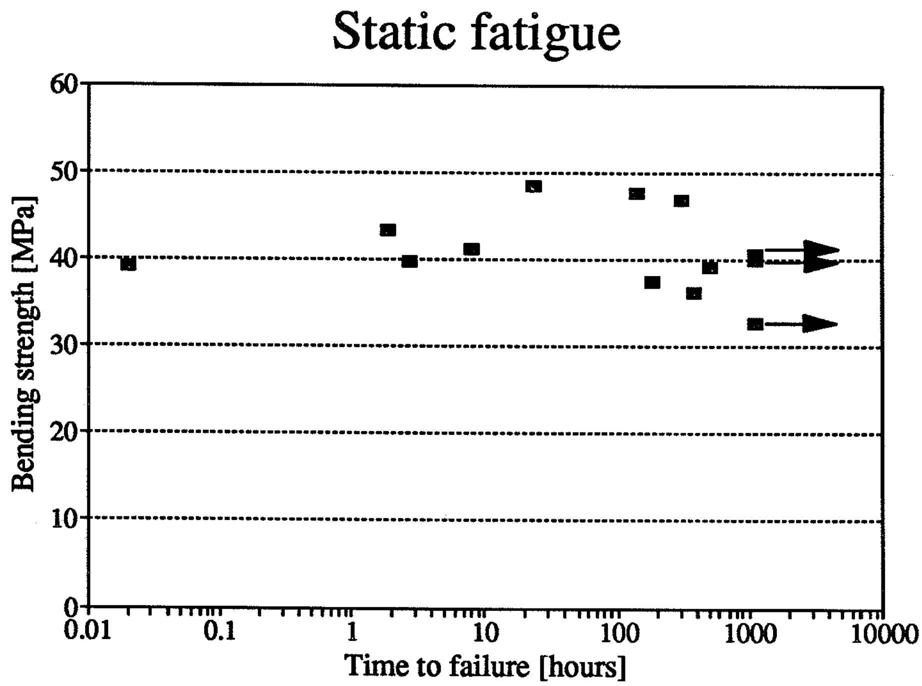

Fig.27 Life time for 13 beams with finger joint failure.

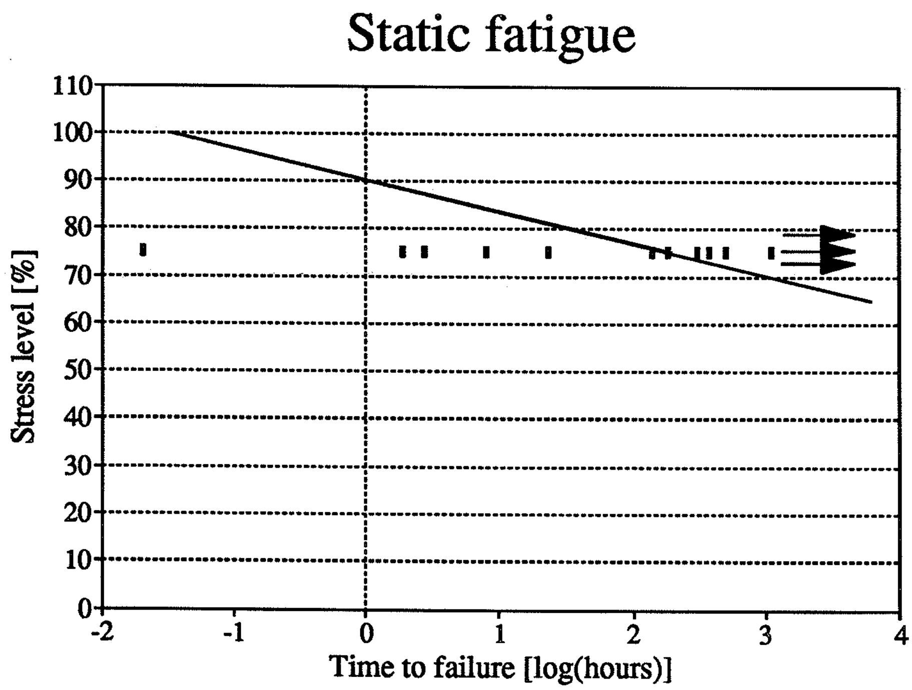

Fig.28 Life time model predicted from the results.

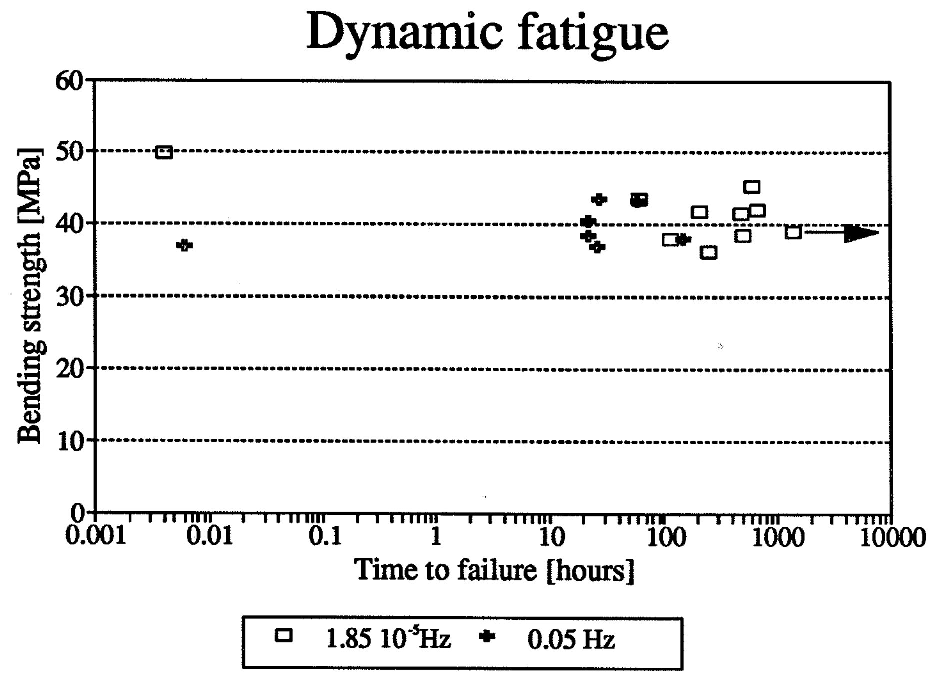

Fig.29 Life times (real time) for beams subjected to dynamic load.

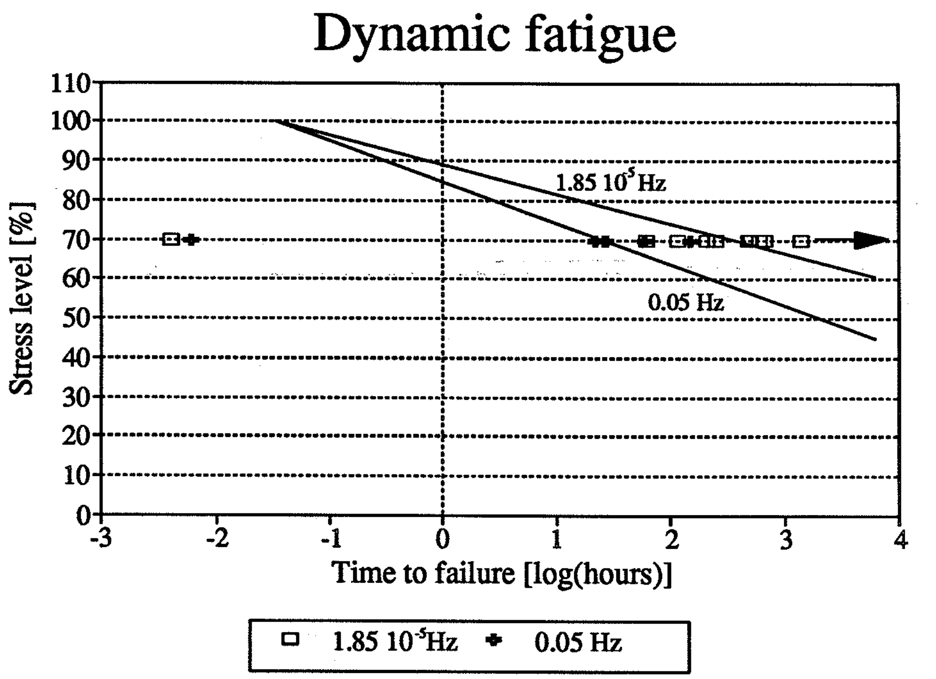

Fig.30 Life time models predicted by the dynamic tests.

5. Conclusions

From the experiments and calculations performed in the two projects, the following main conclusions can be drawn:

- The matching technique used in both projects formed a good basis for estimating strength of twin specimens.
- The weakening of finger jointed timber caused by a high moisture content is similar to the strength decrease of timber without finger joints.
- Data for density and Young's modulus did not correlate very well with the measured strength values.
- The Finite Element Method calculations demonstrated a marked concentration of stresses around the gap at the end of the finger tip. The most favourable distribution of stresses was found for the I-30 and I-40 profiles, as opposed to the I-10 and I-20 profiles, that both had higher stress concentrations.
- A verification of the FEM results attempted through tensile tests was not successful owing to inaccuracy during production of the profiles. Comparison of the results enabled an evaluation of the severeness of various stress types.
- Both FEM calculations and tensile tests demonstrated that rounded finger tips resulted in a higher strength of the joint.
- The static fatigue tests resulted in life time models that were in good agreement with the Madison model. This is illustrated in Fig.31.
- The dynamic fatigue tests showed that the durability of finger jointed timber subjected to a pulsating load is markedly inferior to the durability when subjected to constant long term load. This is illustrated in Fig.32, from which it is evident that the time to failure for all frequencies is considerably shorter compared to the static life times even though the beams were only loaded for half of the elapsed time.
- A higher proportion of glue failure as opposed to wood failure was found in the static and dynamic fatigue tests compared to the short term tests. This is probably due to poor fatigue characteristics of the glue.

The results from the reported projects indicate that the proposed design strength factor of 0.6 is acceptable for static long term load but too high for dynamic long term load.

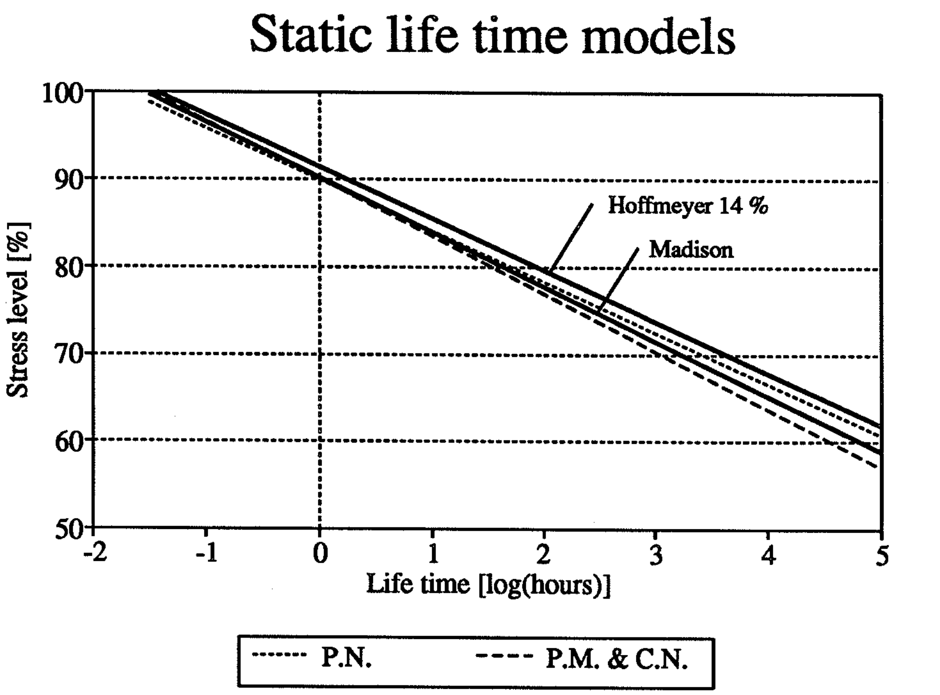

Fig.31 Static life time models from the two projects compared to reference models.

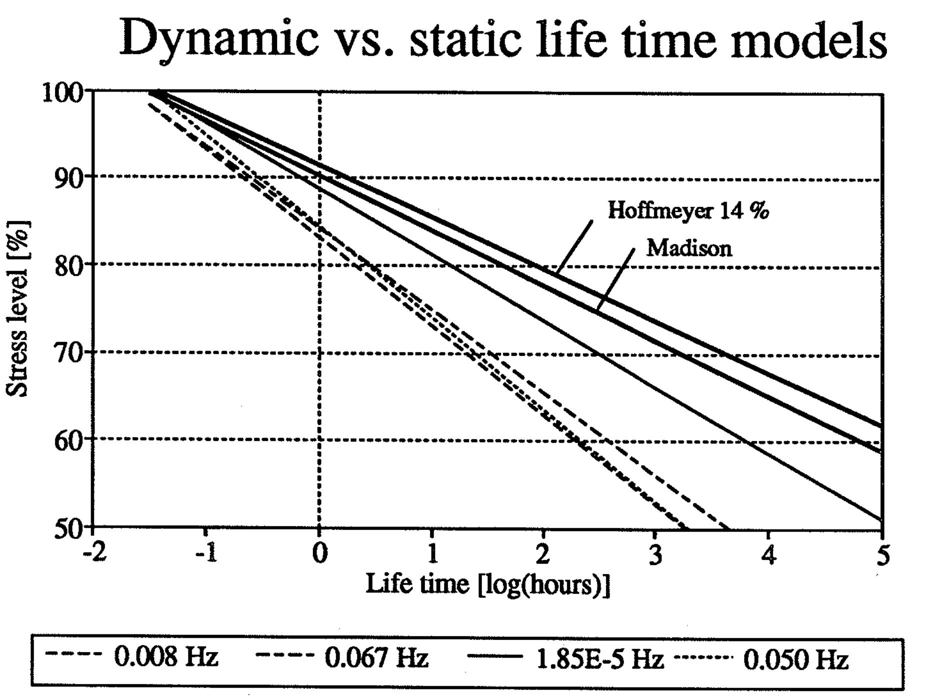

Fig.32 Dynamic life time models compared to static models.

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