STRENGTH OF FINNISH SOFTWOODS IN COMPRESSION PERPENDICULAR TO GRAIN AND REINFORCEMENT OF SUPPORT AREAS WITH NAIL PLATES

Ari Kevarinmäki

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SUMMARY

The test results of load-carrying capacity in compression perpendicular to the grain of the support areas without reinforcement and with nail plate reinforcement are shown in this paper. The density of softwood has a significant effect to the compression strength perpendicular to the grain. The lowest strength values are obtained in the diagonal direction between tangential and radial directions. Usually sawn timber has this weakest direction at support areas in compression perpendicular to the grain. However the strength values of Codes are based on the test results of the main perpendicular directions, and with low-density softwoods these strength values may be about two times too high for the diagonal direction.

A low-cost and easy way to reinforce the chord is to use nail plates at the support areas of the trussed rafter. Although the supporting block is wooden, the bearing capacity will increase at least 30 % with nail plate reinforcement of the chord at an end support because the bearing pressure is of rail type in the supporting structure. If the supporting block is steel, concrete or wood in compression parallel to the grain, the nail plate reinforcement will improve the bearing capacity of the end or intermediate support even 2 times higher. Developed design methods for capacity of support areas reinforced with nail plates are shown in this paper.

INTRODUCTION

Trussed rafters are structures where small support areas are loaded by quite high forces. Usually the truss loads are carried from chords so that compression stresses are perpendicular to the grain. Because the stiffness and the compression strength of wood are rather low in this loading direction the required length of the support area is quite long, sometimes even longer than the width of the supporting structure. This paper is focused on the reinforcement effect of nail plates in the support areas.

TESTING PROCEDURE

A test series of 133 specimens were carried out to test the bearing strength of nail plate structures with nail plate reinforcement at the end and intermediate supports. A reference series of 42 specimens were tested for capacity of support areas without reinforcement. The characteristic strength of each case was calculated from at least 5 parallel specimens.

The main part of tests were done with normal structural size Finnish spruce (*Picea Abies)* of densities 360..400 kg/m^3. Width of the specimens were 45 mm and height 95..220 mm. Some reference tests were done also with the width of 70 mm spruce, with spruce glulam 45 x 225 mm^2 and with Kerto-LVL 39 x 200 mm^2. All specimens were initially conditioned to RH 65 %.

Three different types of nailplates were tested as the reinforcement of the chord: 1) Common nailplate with threaded nails, 2) Common homogeneous nailplate and 3) Nailplate with 3 threaded nails punched from the same hole. The thickness of plates was 1.25..1.30 mm, the length of nails was 13..14 mm, the characteristic strength of steel was 360 MPa or 400 MPa and the punched area of plates was from 26.2 % to 27.4 %. The location of nails was in straight lines in all the tested plates so that unbroken steel lines were in the loading directions. The length of nailplates was 140 mm and they were placed to the chords 45 mm inwards of the support edge. The vertical gap between the nailplates and the bearing surface was on the average 7.5 mm. The test were done with the multipurpose nailplates, which function as joints as well as reinforcement nailplates, and with distinct reinforcement nailplates. The distinct reinforcement nailplates were placed with either 10 or 45 mm vertical gap from the joint nailplates. Examples of the tests are illustrated in Figure 1.

The length of the support area was at the end supports 100 mm and at the intermediate supports 50 mm. The material of the supporting block was steel in the main test series. In reference series also the influence of parallel and perpendicular to the grain compression wooden supporting blocks was studied. The main part of specimens were loaded perpendicular to the bearing surface. Six reference specimens were tested with 3° angle between the chord and the bearing surface. The specimens were loaded to failure or to at least 10 % compression with strain controlled loading speed of 2 mm/min. Initial loading to about 50 % from 'design' value of applied load and down to zero was included in the beginning of the test. The deformation was measured in continous-motion from the bearing surface to the 90 mm level of the chord.

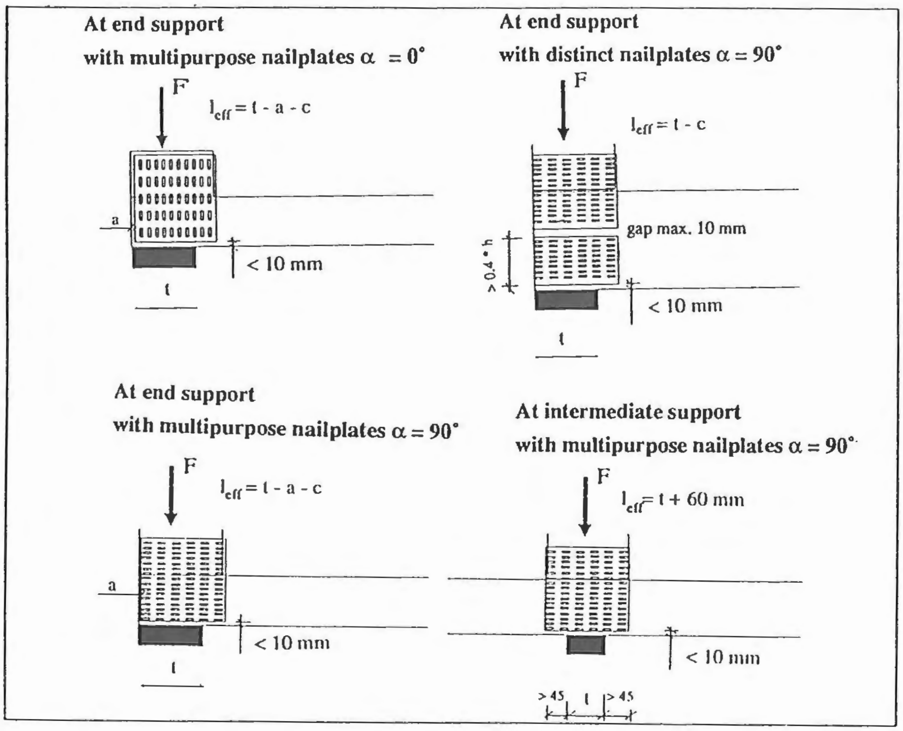


Fig. 1 Loading and measuring configurations of three test series. a) Support area reinforced with 'vertical' multipurpose nail plates at an end support. b) Support area reinforced with 'horizontal' distinct nail plates at an end support. c) Support area reinforced with 'horizontal' multipurpose nail plates at an intermediate support.

TEST RESULTS

Support areas without reinforcement

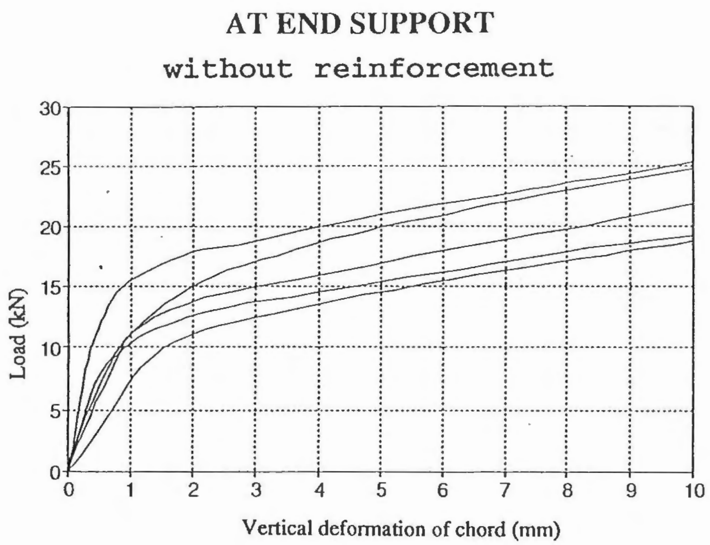
Typical test results of the specimens at the end and intermediate support areas without reinforcement are graphed in fig.2. No failure loads in compression perpendicular to the grain are obtained. But the mean strength value of the test results at the deformation 10 mm was 4.9 MPa with average density 395 kg/m^3. Normally the characteristic strengths are calculated from the compression strain of elastic deformation plus 1 %. With this deformation (1.5 mm..3.0 mm depending of height of the chor) the strength values were at least 30 % lower.

According to the Finnish Codes the strength value of Finnish softwoods in compression perpendicular to the grain is 6.5 MPa in short-term loading in all strength-classes, (FBC 1990). The tests at the end support showed that this value is clearly too high for the rather light density spruce. On the stress level of 6.5 MPa the deformation was generally over 10 %. Although using the compression stresses at deformation 10 mm and taking into account a lower safety requirement in ductile failure, a acceptable characteristic strength of spruce of density 320 kg/m^3 would be 3.3 MPa in compression perpendicular to the grain. Value 6.5 MPa seems to fit to the density of 450 kg/m^3.

The tests at the intermediate support showed that Codes underestimate the capacity of rail type loading in compression perpendicular to the grain. With the Codes coefficient k = 1.316 and compression strength value of 6.5 MPa the calculated capacity of the chord at the intermediate support correspond with the test results of light specimens (380 kg/m^3). By comparing the tests at the intermediate supports to the tests at the end supports it may be concluded that the coefficient k could be about 35 % higher than the value of Codes (for example k = 1.78 with 45 mm chord width).

Test results of the support areas with Kerto-LVL chords showed that compression strength and modulus of elasticity are clearly higher than those of light softwoods. The short-term strength in compression perpendicular to the grain was with the Kerto-LVL (density 470 kg/m^3) 1.9 times higher than the test results of spruce (average density 390 kg/m^3).

Variation of chord height from 95 mm to 220 mm had no effect to the load-strain dependence of the chord. Glulam spruce (45*225 mm^2) had equal behaviour with the same density timber chord. Reference test series with parallel or perpendicular to the a)



b)

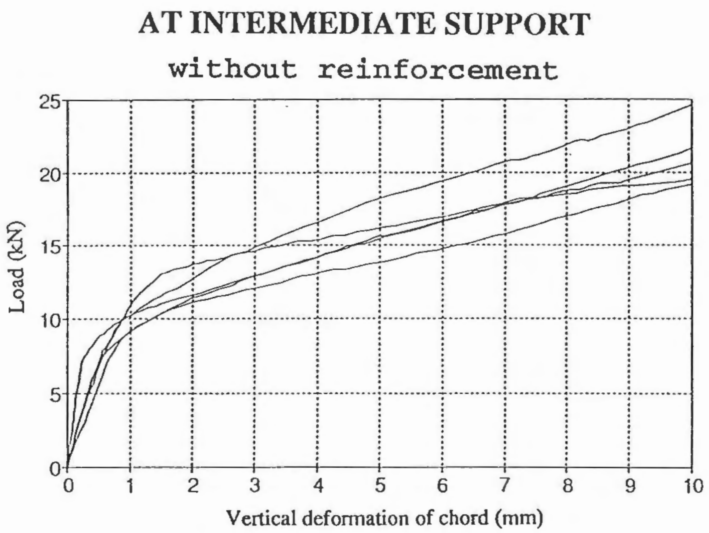


Fig. 2 Measured load-deformation curves of support areas without reinforcement in two test series. a) Chord 45 x 95 mm^2 at an end support 100 mm b) Chord 45 x 95 mm^2 at an intermediate support 50 mm.

grain loaded wooden supporting blocks had no significant effect to the mechanical behaviour of the chords. The load strain dependence results at the middle of the supporting area were similar to the cases of the perpendicular supported chords in the test series where the angle of 3° between the bearing and the chord surface.

Support areas reinforced with nail plates

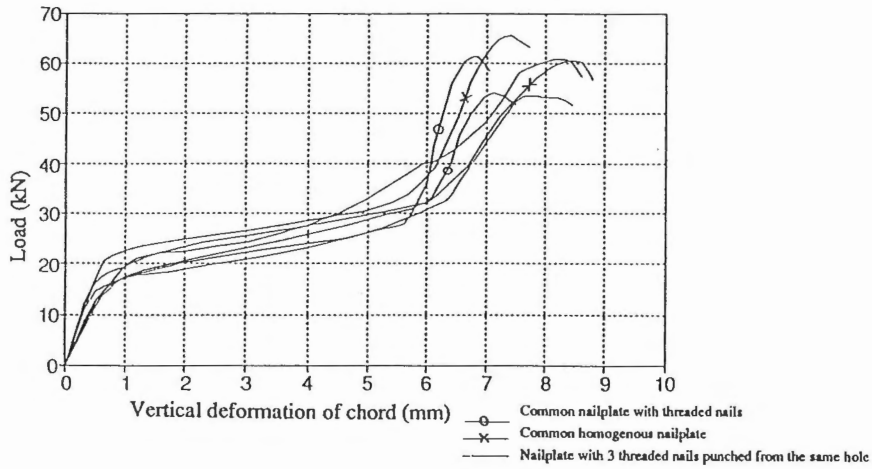
Some tests results of the reinforced specimens are graphed in fig.3 where the load-deformation curves of two test series are presented. The nail plate reinforcement improved clearly the modulus of elasticity of the support area: modulus of elasticity was at both the end and the intermediate support at least 2 times higher than it was on the chords without the nail plate reinforcement. Maximal load of the linear elasticity region was also higher (10..20 %) than in case of the ordinary chords. After the strength in compression perpendicular to the grain of wood has been exceeded the stiffness of the support area decreases and the wood compresses at the gap between the nail plates and the bearing surface to about half of its original height. When the pressure is so high that the wood cell structure has collapsed in the gap region, the nail plates carry the loads together with timber and the stiffness of support area increases again. Load carrying capacity is achieved when the nail plates are buckling. That requires about 3 % vertical strains in the nailplate area of the chord.

Test result of the nail plate reinforced chords are analyzed by subtraction of the load carrying capacity of wood and the buckling load of nailplates in the tests. The short-term characteristic strengths of the nail plate reinforcement were calculated from the 5 % fractile. The long-term strengths are obtained by dividing the short-term strengths by a factor 1.3. According to the test results the load-carrying capacity of the support area with the nail plate reinforcement may be calculated as a sum of the wood strength in compression and the reinforcement strength of the nail plates. Fundamental properties of all the tested nailplate types were so similar that there were no significant difference between the test result of the studied nailplates.

The best reinforcement capacity of the nail plates was achieved when the nail plates had been placed in their main direction $\alpha = 0°$, because then the loaded steel area is maximal. The buckling occurred in this direction in one line between consecutive nails of plate and the buckling force was about same than in nail plates of a joint with a gap between timber parts. The characteristic strength of nail plate reinforcement is so high in this plate direction that the load carrying capacity of the support area will increase 96 a)

AT END SUPPORT

with nail plate reinforcement



b)

AT INTERMEDIATE SUPPORT

with nail plate reinforcement

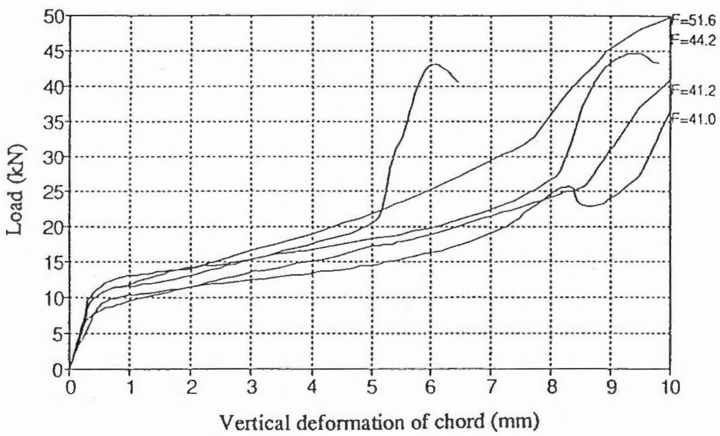


Fig. 3 Measured load-deformation curves of support areas with nail plate reinforcements in two test series. a) Chord 45 x 95 mm^2 reinforced with 'vertical' multipurpose nail plates at an end support 100 mm. b) Chord 45 x 95 mm^2 reinforced with 'horizontal' multipurpose nail plates at an intermediate support 50 mm.

% in the width of 45 mm chord with nail plates placed on both sides of chords in direction $\alpha = 0°$ to the whole length of the support area.

The plate buckling has a different mechanism in the support area with 'horizontal' ($\alpha = 90°$) placed nail plates than with 'vertical' (a = 0°) placed nail plates. Because the distance between the nails is shorter in the plates 'horizontal' loading direction the buckling area is large and almost the whole plates are curling in buckling. The average normal stress of the unbroken steel areas of the nail plates was 220 MPa in buckling of 'horizontal' reinforcement plates. According to the test results the load-carrying capacity of the support area increases 60 % with 'horizontal' placed nail plates reinforcement in the width of 45 mm chord. This additional capacity is obtained with a rather heavy spruce (about 450 kg/m^3), but with light spruce the relative additional capacity is much higher.

Using the distinct reinforcement nail plates the deformation of the chords are bigger than in the chords with 'multipurpose' nail plates because wood compresses in the gap between nailplates before the nailplates are actually carrying loads. According to the test results the gap between the reinforcement and the joint nailplates should be less than 10 mm. At the end support the buckling strength of the distinct reinforcement plates is about 40 % lower than the buckling strength of the multipurpose nailplates because wood is expanding horizontally in the gap between nailplates. This causes earlier buckling. At the intermediate support the spreading of wood is lower and the capacity of the distinct nail plates is almost same than the capacity of the multipurpose nailplates if the height of the distinct plates is sufficient (at least about half of the chord height).

If the length of the reinforcement nail plates is longer than the length of the support area, the load-carrying capacity is clearly higher than the buckling strength calculated according to the support length. According to the test at the intermediate support where nailplates are placed 45 mm over both of the support borders the effective reinforcement length of nailplates was the support length plus 60 mm. If the length of nailplates is sufficiently long the capacity of the support area is rather high at the intermediate support; for example with the support length of 50 mm the capacity of the chord (45 mm) will increase 160 % ($\alpha = 0°$) or 100 % ($\alpha = 90°$) by using correctly placed nailplates in the reinforcement of the support area.

The wood gap between the nailplates and the bearing surface has a high influence on the deformation of the support area. However the influence to the loading capacity is almost insignificant. The gap should be as small as possible to minimize the deformation at serviceability limit state. If the gap is zero the load-deformation curve is linear also after the compression failure strength of wood has been exceeded. That will occur when the total compression strain of the chord is about 3 %.

According to the test results the height of the chord has no dependence on the mechanical behaviour of the support areas. The width of the chord however has a great effect to the reinforcement capacity of the nailplates because buckling occurs much earlier in the wide chord where the value of horizontal spearing of the chord is bigger. In reference test series of 70 mm chord width the strength of reinforcement by average was only 61 % from the strength of the reinforcement of the chord width 45 mm. All strengths of the nail plate reinforcements shown in this paper may be applied only with the chord widths below 50 mm.

The capacity of the nail plates reinforcement with the Kerto-LVL chords was almost zero in the tests. In compression perpendicular to the grain the Kerto-LVL has a brittle fracture mode where the ultimate strain is so small that the nail plates don't yet carry the loads. The support areas may be reinforced with nail plates only when the strain ability of the chord is so large that the compression strain may increase to 3 % in the nail plates. For example the nail plate reinforcement of timber is not possible in compression parallel to the grain.

COMPRESSION STRENGTH PERPENDICULAR TO THE GRAIN

Generally codes overestimate clearly the compression strength perpendicular to the grain with rather light softwoods because the codes values are based on the test results of tangential direction and it doesn't take account the density of wood. However the compression strength is 30 - 40 % lower in the diagonal direction (45°) between tangential and radial directions than in the tangential direction, (Siimes & Liiri 1952), because the regular wood cells are buckling much earlier in diagonal compression than in compression parallel to the cell walls. Squared timber is usually sawn from near the centre of log, and then the worst diagonal direction is found in compression of the chord perpendicular to the grain. This is shown also in compression tests with glulam specimens where the mean strength value perpendicular to grain was 2.8 MPa with 1 % plastic deformation, (Feldborg 1991).

The compression strength perpendicular to the grain has the same value for all strength classes in Finnish Codes. However it may be verified by analysing woods cell structure that the perpendicular compression strength has a direct dependence to the square of relative density, (Gibson & Ashby 1988):

$$\sigma_{\perp} = C\,(\rho/\rho_s)^2 .$$

Where: ρ_s is the density of woods cell wall material.

This calculated dependence is shown in In fig. 4 where a fixed point is 395 kg/m³ and 0.63 (relative strength, that was the characteristic strength of test results dividing by the Codes value). The density of the cell wall material is about 1500 kg/m³ (Koponen & Al 1989). The relative test results of Siimes & Liiri in the tangential, diagonal (45°) and radial directions are shown also in fig. 4. These test results have been fixed also to the same point (395 kg/m³, 0.63). Fig. 4 shows that the theory of relative density has good agreement with the test results.

A design proposal for utilization level reduction

A proposal for the maximal recommended utilization levels of the compression strength values perpendicular to the grain presented in Finnish Codes is given for different strength classes in table 1. These values have been calculated using the measured compression stresses at deformation 10 mm, taking into account a lower safety requirement due to the ductile failure in the characteristic strength and using the theoretical density dependence. The calculations have been done for spruce with the minimum requirements of the strength classes densities.

Table 1. The maximal recommend utilization levels of the compression strength values perpendicular to the grain of Finnish Codes for different strength classes, (Kevarimäki 1991c).

T18	T24	T30	T40	L30	L40
51 % >320 kg/m³	67 % >370 kg/m³	87 % >420 kg/m³	100 % >470 kg/m³	87 %	100 %

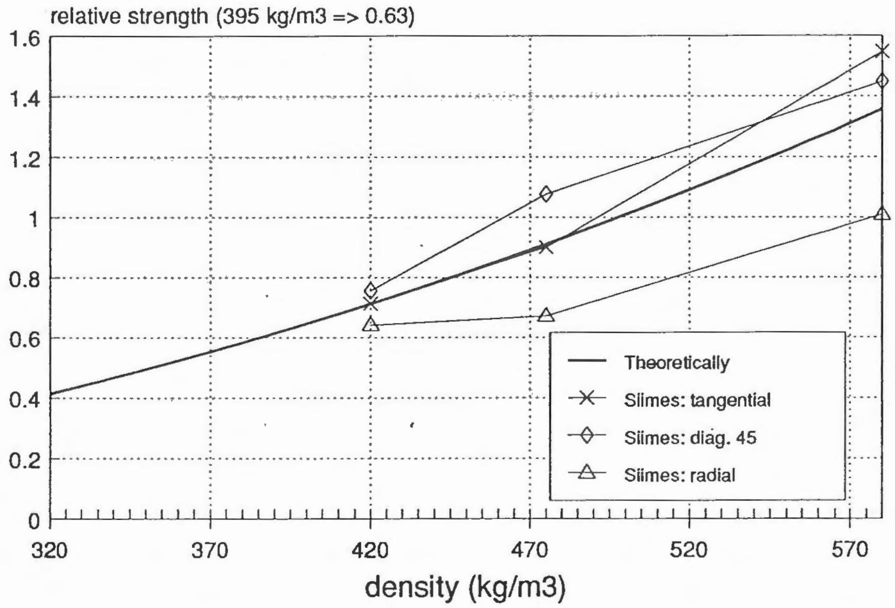


Fig. 4 The theoretical density dependence of the compression strength perpendicular to the grain and the relative results of test series made by Siimes & Liiri (1952). Fixed point is 395 kg/m^3 and 0.63 for all curves (extrapolation for the test results).

A DESIGN METHOD FOR CAPACITY OF SUPPORT AREAS REINFORCED WITH NAIL PLATES

Requirements of properties and geometry of the nail plates

The strength value of the reinforcements are given in this paper for nail plates that fullfill the following:

- Characteristic strength of the steel is 360..400 MPa (Z36, Z40)
- The thickness of nail plate is at least 1.20 mm
- The length of the nails is 12..15 mm
- The punched area of the plate is 25..30 %
- The punching direction of the nails is parallel to the main direction of the plate
- The location of nails is so that there are unbroken steel lines in directions $\alpha = 0°$ and $\alpha = 90°$.

Location requirements of the reinforcement nailplates

- The nailplates are placed symmetrically on both sides of the chord
- The loading direction of the nail plates is $\alpha = 0°$ ('vertical' plate orientation) or $\alpha = 90°$ ('horizontal' plate orientation).
- The distance between the chord soffit and the underedge of the nailplate is at most 10 mm (maximal tolerance).
- Using distinct reinforcement nailplates the gap between upper and under nailplates should be at most 10 mm and the height of distinct nailplate should be at least 40 % from the height of chord.

Requirement of the chord

- The chord is strength classed softwood (density over 320 kg/m^3) sawn timber or glulam.
- The angle between load direction and the grain of chord should be 70°..90°.
- The width of chord should be at most 50 mm.

Load-carrying capacity of support area reinforced with nail plates

The capacity of the support area is calculated as a sum of strength of wood in compression and the strength of the nail plate reinforcement:

$$F_d = A_t\, \sigma_{c\perp d} + 2\, l_{eff}\, p_{c\perp\alpha d}$$

Where: A_t is the area of support surface,
$\sigma_{c\perp d}$ is the design strength of wood in compression perpendicular to the grain (includes a possible strength increasing in rail type loading),
l_{eff} is the effective length of reinforcement (see fig.5) and
$p_{c\perp\alpha d}$ is the design value of nail plate reinforcement (given in table 2.).

At an intermediate support where the nail plates are placed at least 45 mm over both support edges, as the effective length (l_{eff}) may be used value t + 60 mm, where t is the support length. In other cases the effective length should not exceed the support length.

If the full reinforcement strength is utilized, the capacity of the supporting block must be high enough. If the supporting structure is wood in loading direction perpendicular to grain, the bearing strength of the supporting block will be a critical factor at the end support with all presented reinforcements cases of the chords.

Strength values of nail plate reinforcements

The characteristic strengths of nail plate reinforcements are given in table 2. These values are for medium-term loading (time class B). Strengths for short-term loading may be calculated by multiplying these values by a factor 1.3. The design values of the ultimate limit state are calculated with a partial safety factor $\gamma_m = 1.3$.

The distinct reinforcement may not be utilized if the loading direction of the joint plates are not parallel to the main direction $\alpha = 0°$ or $\alpha = 90°$. If the distinct reinforcement plate is placed in other direction than the upper joint nailplate, the value $p_{c\perp 90k}$ is used as the strength of reinforcement.

Table 2. The characteristic strength of nail plate reinforcements for medium-term loading in service class 1 and 2.

	At end support		At intermediate support	
Direction of plates	$\alpha = 0°$ $p_{c\perp 0k}$ [N/mm]	$\alpha = 90°$ $p_{c\perp 90k}$ [N/mm]	$\alpha = 0°$ $p_{c\perp 0k}$ [N/mm]	$\alpha = 90°$ $p_{c\perp 90k}$ [N/mm]
Multipurpose	**108**	**67**	**108**	**67**
Distinct	**65**	**40**	**108**	**67**

Compression strength at end support

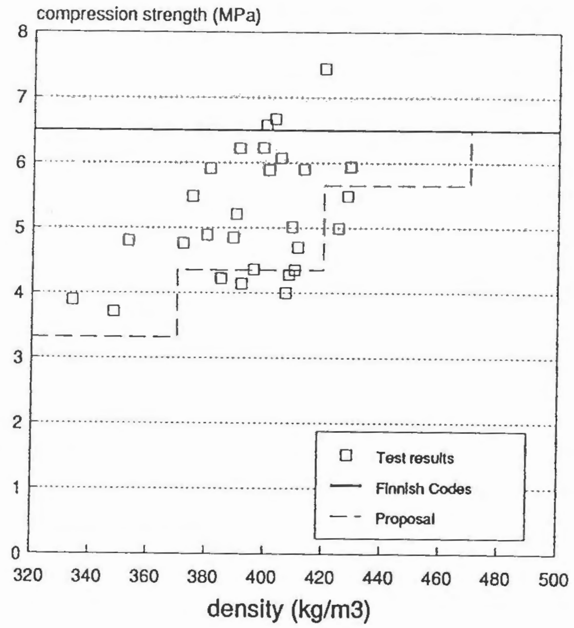


Fig. 5 The test results at deformation 10 mm of specimens without reinforcement at the end support, characteristic strength value of Finnish Codes in short-term loading, and a proposal for the maximal recommended utilization levels of characteristic compression strength perpendicular to the grain.

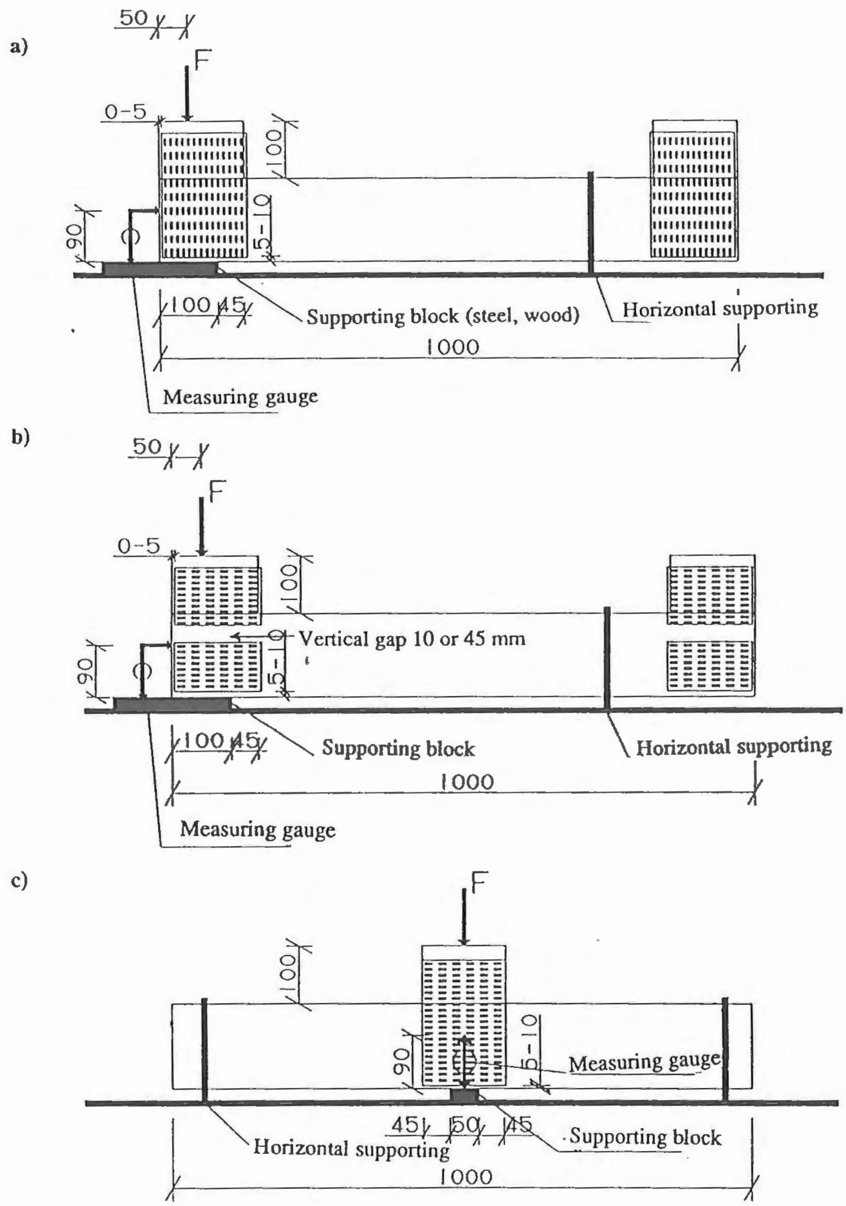


Fig. 6 Different kinds of nail plate reinforcements and the effective lengths (l_{eff}) of reinforcements. Value c is tolerance.

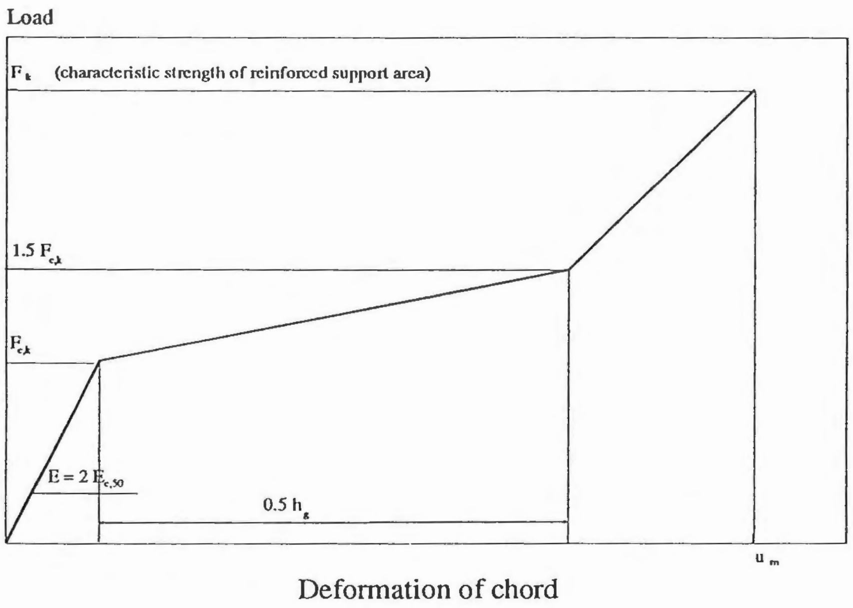


Fig. 7 The simplification load-deformation curve of reinforced support area. Force $F_{c,k}$ is characteristic capacity of wood in compression perpendicular to the grain. $E_{c,50}$ is the appropriate modulus of elasticity of wood. Value h_g is the height of unreinforced wood gap. Failure deformation $u_m = 0.5\,h_g + 0.03\,h$, where h is the height of chord.

The deformation of support area reinforced with nail plates

The strain of a reinforced chord may be estimated according to the figure 6. The mean value of deformation is calculated from the graph by applying the maximal load without any safety factors in the serviceability limit state.

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Ari Kevarinmäki, M.Sc. (Eng), Research Engineer
Laboratory of Structural Engineering and Building Physics
Department of Civil Engineering and Surveying
Helsinki University of Technology