ABSTRACT: Extrapolation of design rules meaning application outside the experimentally verified range is questionable. For this reason design rules based on physical models are preferable when available. This study shows that a physically based stress spreading model can successfully be applied for a wide range of practical design situations. The credibility of this model is based on experiments, FEM and optical techniques used to assess and quantify the strength affecting parameters. It model applies to local supports and stressed areas below concentrated forces. It is shown that the affected area is limited and that for this area the stress spreading model predicts the test results very well in contrast to expectations by design rules of EU, US and Aus/NZ. This model is a potential candidate to be incorporated in future structural timber design standards.

KEYWORDS: Support, timber, perpendicular, stresses, load transfer, wood.

1 INTRODUCTION

Many authors have reported compressive perpendicular to grain tests an issue as old as the structural problem of a simply supported beam. In the 19th century, with the introduction of the railway ties, many tests must have focused on the bearing resistance. In the early 20th century, engineered wood structures required knowledge of the bearing capacity caused by concentrated loads. An example can be found in timber light-frame construction where timber rails are supported and locally loaded by studs, Figure 1. In those years, the permissible strength design method was based on the proportional strength limit, Kolmann et al[1]. An historic overview of some late 19th and early 20th century research efforts for the parameters that affect the bearing strength, are presented by H. Kühne [2]. Gehri argued that differences in the determination methods applied by the test standards around the globe, lead to a confusing situation where test results become incompatible. On every continent, these incompatible test results are then used for empirical structural design models to determine the bearing capacity for a given structural detail. Regardless of which standards are used, the bearing capacity predicted should not differ too much, although some models are more conservative than others. None of the empirical models consider the support condition of the beam subjected to concentrated loads. In Fact, the complexity of the problem has forced many design codes’ committees to accept an engineering (empirical) approach. Recently, a successful attempt was made to apply an elastic-fully plastic stress spreading model to determine the bearing capacity by Van der Put [4]. His model, initially develop for the expanation of the embedment capacity of dowel type fasteners in particle board, was later on used for the determination of the bearing capacity of continuously supported timber beams, Figure 2. For this application the stress spreading model is superior to any of the previously published empirical models. The study described in this paper...
concentrates on the applicability and credibility of the model for non-continuously supported beams. The theory presented has as starting point that wood can be regarded as isotropic plastic material with uni-directional reinforcement which does not contribute to perpendicular and shear deformation. The slope of the spreading stresses depends on the deformation considered, Figure 2.

Figure 2: Continuous supported top loaded beam.

Assuming coniferous wood species and a 3% to 4% deformation, the slope is 1:1 and for 10% deformation 1:1.5. According to Van der Put, the model may also be applied to situations where the support length is limited but in line with a load on the opposite side of the beam, Figure 2.

Evaluation of additional tests from many literature sources added more credibility to this model, Leijten et al [5]. It was concluded that the stress spreading model is superior to any of the previously published empirical models and a potential candidate for introduction in future structural design codes.

2 THE STRESS SPREADING MODEL

Models for continuously supported beams that are based on spreading of the bearing stresses are not new. In 1983, Madsen et al [8] performed numerical simulations and concluded that the bearing stresses dispersed not beyond 1.5 times the beam depth, which exactly corresponds to what Van der Put [4] derived theoretically. The same was reported by Riberholt [9]. Only in his analytical stress spreading model, Van der Put was able to take account of this phenomenon. As an important starting point and reference, the stress spreading model takes the standard compressive strength, $f_{c,90}$ of a test specimen (prism) loaded over its full surface (experimental set-up according to European standard EN408). Reason being that the physical theory requires physically correct strength values. The test specimens to determine the compressive strength perpendicular to grain in North America (ASTM), Australia and New Zealand are different. These test specimens are fully supported and centre loaded over part of the surface (as in principle is shown in figure 2). These are so-called empirical or technological tests to cover most common load situations with no intention to reflect any physical correct property. For a practical situation, where the loaded area is equal to the beam width, the stress spreading model reads:

$$\frac{F_d}{b l} = \sqrt{\frac{1}{\pi} f_{c,90}} = k_{c,90} f_{c,90}$$

(1)

Where:
- $F_d$ = the load, in Newton,
- $l$ = the contact length of the applied load in grain direction in mm,
- $b$ = the width of the beam in mm,
- $l_{ef}$ = the effective stress spreading length at the support in grain direction in mm,
- $f_{c,90}$ = the standard compressive strength perpendicular to the grain in N/mm$^2$.

Originally Van der Put added a correlation factor of max. 1.1 to $k_{c,90}$. The validity of the equation is restricted as in the case of beams with a high aspect ratio (beam depth to width), because other types of failure may occur before the compressive capacity is reached, as e.g. rolling shear, Basta [6].

A category of beams where the compressive or bearing strength capacity is also important, are beams that are not continuously supported, but only locally as with the beam in Figure 3. The subject of this study concentrates on application of the stress spreading model for these particular situations.

Figure 3: Local supports

3 BEAM LOADED BY CONCENTRATED LOADS

There is no difference between the bearing capacity of a beam running over a support or under a load plate. In both cases, a force acts on one edge of the beam without finding direct support on the other edge, such as in a simply supported beam loaded by a concentrated load between the end supports. To evaluate the stress spreading model for concentrated load cases, a research project was carried out by De Leijer [7]. Laboratory experiments were complemented by numerical and optical tests and a summary of his results is presented. The beams tested varied in depth and span from 145 mm and 590 mm for sawn timber up to glued laminated beams of 600 mm depth and 1170 mm span.

3.1 EXPERIMENTAL PROGRAM

The wood species for all specimens was Nordic Spruce. The mean density and modulus of elasticity was 440 kg/m$^3$ and 10700 N/mm$^2$ for the sawn pieces and 445
kg/m³ and 12141 N/mm² for the glued laminated test pieces, respectively. The modulus of elasticity was determined using the Timber Grader by Brookhuis Electronics (based on dynamic wave propagation technology). The grade assigned by the Timber Grader was C24 for the sawn timber and G24h for the glued, laminated pieces. Strength class C24 means a lower 5% fractile or characteristic bending strength and compressive strength perpendicular to grain of 24 N/mm² and 2.2 N/mm² respectively. This is a standard grade for Scandinavian timber. Starting point for the lab tests was the single supported beam loaded by a concentrated load at mid span. The background for the choice of test specimen dimensions was that neither bending nor shear failure should govern but only the bearing capacity. To take a realistic first step the concentrated load at mid span acts over a bearing length of 100mm in grain direction and over the full beam width. The sawn timber specimens were cut from 145 mm and 220 mm depth and 3000 mm length boards.

![Figure 4: Specimens of sawn timber](image)

Two test Series A and B, were produced with sawn timber, depth 145 and 220 mm, to span 590, 880 and 1170 mm respectively, Figure 4. The specimen and span were taken so as to prevent premature failure by shear and bending. Two test Series C and D, were produced with glued laminated timber, depth 400 mm and 600 mm respectively, Figure 5. The spans were identical to the sawn timber specimen.

![Figure 5: Specimens of glued laminated timber](image)

3.2.1 Indentation depth

The study was aimed at answering the question as to how the bearing stresses spread under a concentrated load. The simulation limits were set by the maximum bending stress (stress limit) of the timber beams or by large crushing of the timber fibres (deformation limit) under the concentrated load up to 10% of the beam depth. To analyse the stress spreading in both parallel to grain and perpendicular to grain direction, the deformation patterns were examined as follows:

To investigate the penetration depth of the perpendicular to grain bearing stresses, the deflection at regular 10 mm spaced cross-sections along the span was evaluated. In Figure 6, the vertical axis represents the deflection of a test beam with a depth of 145 mm. On the horizontal axes the depth of the cross-section is plotted from left to right. The deformation of compressive fibres at the beam top is at the left vertical axis and at 145 mm the deformation of the bottom or tensile fibres. The maximum deflection (U22) is 8.4 mm for the lowest line. This line represents the deflection of the top edge fibre at the mid span cross-section (directly under the applied load) relative to the lower edge of the beam which is in fact the deflection including the indentation by crushing perpendicular to grain fibres. This deformation decreases for fibres of a particular cross-section that are more distant from the top, as the line along the horizontal axis decreases to about 2 mm at 50mm from the top edge. The deflections of subsequent fibres going down the cross-section remain nearly constant as the indentation portion in the deflection is gone. For a cross-section near to the support, there is nearly no deflection at all. This is represented by the top line in Figure 6. Caused by the rigidity of the steel plate under the applied mid span load, the deflection of some of the near mid span cross-sections also start at 8.4mm. A gradual change is noticed for the cross-sections further away from the loaded area as the effect of the indentation decreases. For verification of the FEM deformation results, the optical ESPI laser technique was used during the laboratory tests. After some data processing, graphs like Figure 7 were found. This specific graph originates from the third specimen of Series A2. Similar graphs were found for the simulations continued to consider the test series. The so called Hill yield criterion was applied and, despite its shortcomings to represent the timber behaviour in detail, the final results corresponded well with previously reported simulations by Lum and Karacebeyli [10].

3.2 NUMERICAL MODELLING, OPTICAL VERIFICATION AND LABORATORY TESTS

To study and analyze the stress distribution, the commercial FEM program Abaqus was used to simulate the behaviour of the test series. This choice for this particular commercial program was made based on its user friendliness and the available expertise in our research group.

After initial tuning, the results of the simulations were in agreement with the load-displacement curves of the test on fully surface-loaded standard prismatic specimens.
the other specimens. It could be concluded that the lines of both Figures 6 and 7 are in agreement with each other. Both prove that at 50mm depth in the cross-section, the indentation by bearing stresses perpendicular to grain vanish, and all that remains are bending deflection deformations. This transition is marked in Figure 7 as a bold line. Below this line, the indentation at that point of the cross-section increases the total deflection.

Figure 7: Results optical detection of indentation depth, for test A2

As for test Series A, the same numerical procedure was followed and backed up by the optical detection method for the test Series B, C and D. The same method of determining the indentation depth was carried out for the specimens of all other Series. Although the indentations at the surface increase up to 35 mm for the glued laminated test beams of Series D, the indentation depth did not increase with increasing beam depth but attained a maximum of 140mm.

3.2.2 Indentation length

The extent to which the indentation stretches along the grain was analysed in the same way as the indentation depth. Horizontal sections spaced over the depth of the beam show how far the bearing stresses reach outside the loaded area, Figure 8. The top line represents the bottom fibres which show the deflection of a beam subjected to bending with a maximum of 2mm at mid span. Consecutive lines represent the deformation of the fibres closer to the top of the beam, clearly showing the increasing indentation. The bottom line of the top beam fibres obviously is straight for 50mm, which is half the bearing length of the steel plate. Again, at a certain depth, indentation deformations add to the bending deflections. For this particular test, specimen A2, the onset of indentation is 50mm from the top edge while the indentation length in grain direction was arbitrarily set to 120mm from mid span, indicated by the arrow in Figure 8. Both values are observed at a design bending strength load level. Similarly, the FEM curves were confirmed by the optical ESPI test technique, Figure 9. The bolt line shows the deflection when the indentation has disappeared. The same procedure was followed for the other test Series, B, C and D. In the same way, as for the indentation depth, the indentation length reached a limit despite the increasing specimen dimensions indicated, as no differences were observed for Series C and D. A comparison between the numerically predicted and optically observed indentation depth and length along the grain shows agreement. The spreading angle of the bearing stresses can be easily derived based on these results. The mean of these values compares very well with the theoretically derived value of 1.5 by Van der Put [5]. It should be noted, that when the bending deflection become smaller, it becomes more difficult to distinguish where the indentation contributes. In other words, the interpretation of the ESPI test results is not so successful for the Series C and D. Figure 10 shows the indentation depth versus beam depth for both methods.

Figure 9: ESPI detection of indentation depth

Because the FEM results correspond well with the optical observed results for the Series A and B, more
credibility is given to the FEM results for Series C and D.

### 3.2.3 Model verification

From Figure 10 it follows that the maximum indentation depth \( h_e \) can determined by Eq. (2) and the maximum spreading length \( l_{ed} \) by Eq. (3).

\[
h_e = 0.35h \leq 140 \text{ mm} \tag{2}
\]

\[
l_{ed} = l + 2 \times 1.5 \times h_e = l + 3h_e \tag{3}
\]

The stress spreading model of Eq. (1) is valid for an indentation of the loaded edge of 10% of the indentation depth, being 8.8 mm for Series A and B and 14 mm for Series C and D. In Figure 11, the result of the stress spreading model using Eq. (1) with \( l_{ed} \) according to Eq. (3) is presented as well as the test data. Both are in total agreement. The solid wood data and glued laminated timber data, set with a load at 10% deformation of the spreading depth of approximately 20 kN and 50 kN respectively, can be distinguished from each other. For comparison, the predictions according to the model given in Eurocode 5 2008-A1 [11] are given as well, which are clearly above the diagonal and may be attained for deformations far beyond 10%.

Figure 11: Model comparison

For the sawn timber specimens, Eurocode 5 overestimates the load by 20 to 40% for Series A and B and 25% for the glued laminated specimens.

### 4 CONCLUSIONS

The numerical modelling, optical verification and laboratory tests were in good agreement and showed that only a limited part of the beam is actually actively involved in contributing to the bearing capacity. Taking this phenomenon into account the stress spreading model Eq. (1), with \( l_{eg} \) according to Eq. (3), was applied and the following conclusions were drawn.

1. For non-continuous supported beams loaded perpendicular to grain the spreading of bearing stresses is limited to a certain area.
2. The stress spreading model Equation (1) can be applied to the stress affected area. Based on the observed indentation depth \( h_e \) and indentation length \( l_{ed} \) according Eq. (2) and (3) respectively.

For coniferous wood (Spruce), the bearing area \( h_e * l_{ed} \) is restricted; \( h_e \) to 40% of the beam depth \( h \) with a maximum of 140 mm and \( l_{ed} \) to \( l + 3h_e \).

3. Comparing both the stress spreading model by Van der Put [4], which accounts for the bearing stress area, and the model in Eurocode 5:2008-A1, the stress spreading model, Equation (1), leads to a better agreement with the experimental results.

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