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Citation for published version (APA):
Leijten, A. J. M. (2015). Compressive capacity perpendicular to grain of fully supported timber beams of Poplar - model comparison. In Y. M. Haddad (Ed.), *AES-ATEMA'2015, 25th International Conference Advances and Trends in Engineering Materials and their applications, 10-14 August 2015, Torpmto, Canada* (pp. 39-45). Advanced Engineering Solutions.

Document status and date:
Published: 01/01/2015

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
• The final author version and the galley proof are versions of the publication after peer review.
• The final published version features the final layout of the paper including the volume, issue and page numbers.

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Download date: 28. Sep. 2023

A. J. M. Leijten / Proceedings, TORONTO'2015
AES-ATEMA 25th Int. Conference, Toronto, CANADA, August 10 - 14, 2015, pp. 39 – 46.

ISBN 978-1-927838-15-0 (CD-ROM) & 978-1-927838-14-3 (Hard Copy)

[KEYNOTE LECTURE]

AES ATEMA'2015 Toronto, CANADA

TORONTO'2015 AES-ATEMA 25th International Conference
"Advances and Trends in Engineering Materials and their Applications"
(Toronto, CANADA: August 10 – 14, 2015)

Compressive Capacity Perpendicular to Grain of Fully Supported Timber Beams of Poplar–Model Comparison

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Abstract

In timber frame structures, for both residential and multi-storey purposes, timber elements are loaded perpendicular to grain. In the past, structural design code calculations were based on pre-set permissible strength values, applying empirical models with obscure background. Modern ultimate limit state structural design codes, like the Eurocode 5 (EC5) for timber structures, aim at using models that reflect "real" material behaviour. As more experimental results emerge, however, the reliability of the implemented EC5 model is questioned more and more. In the last decade a number of new models have been proposed. One is based on a fundamental principal, the so-called stress dispersion model, but the others are still empirical.

This study shows the physically based stress dispersion model to be more reliable in predicting the bearing capacity of poplar for a wide range of practical design situations, than the empirical model of EC5.

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Keywords
Bearing, compression, perpendicular, timber, poplar, Eurocode.

1 Introduction

Many authors have reported compressive perpendicular to grain tests to be an issue as old as a beam on two supports. 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 still be found in timber frame construction where horizontal timber beams are continuously or locally supported and loaded by studs transmitting the loads from above, Figure 1.

Figure 1. Bottom rail loaded perpendicular to grain by studs.

Gehri [1] argues that differences in the standard world-wide test methods of the compressive strength, lead to a confusing situation leading to incompatible test results. On every continent, these incompatible test results are then used by various empirical structural design models, to determine the bearing capacity. Regardless of which model is used, the prediction as such should not be different and should reflect the actual material behaviour. Another problem is that none of the empirical models consider all types of load situations. For this reason many design code committees use regulations based on simple, but also questionable, engineering approximations.

1.1 The Problem

The latest version of the European structural design code, Eurocode 5: 2008 [2], contains detailed design rules for the compressive capacity perpendicular to the grain. These design rules originate from a model by Madsen [3], later modified by Blass & Görlacher [4]. Van der Put [5] was the first to publish a physical model based on the equilibrium method, assuming linear elastic-plastic material behaviour. Tests performed by Leijten and Larsen [6] on Spruce showed that the Van der Put model has more reliable results than the existing Eurocode 5 [2]. No studies have been published considering wood species other than Spruce-Pine-Fir. So the question that arises is whether the Van der Put model also applies to other wood species. Prior to the introduction of the Eurocode 5 in Scandinavia, a standard compressive strength perpendicular to the grain for Spruce of 7 MPa was used, which is much higher than 2.8 MPa now in Eurocode 5. The reason for this big difference is unknown. Presumably this high value results from a soft calibration procedure which compares an old calculation model with Eurocode 5 in which the standard compressive strength was used as a fitting parameter instead of a material strength property. There might also be other reasons. In EN408 a deformation-controlled test is prescribed to determine the standard compressive strength. The old Scandinavian method might rely on a force-controlled test. This asks the question if load-controlled tests result in higher results than do deformation-controlled tests.

1.2 The aim of the research

The research reported here aims at resolving two issues. Firstly, are the Eurocode 5 and Van der Put models reliable and accurate for low density deciduous wood species like poplar? Secondly, to what extent are the loading test conditions of importance? The two loading conditions are the load-controlled test and the deformation-controlled test procedures. For both cases the test results should be within the region of 300s± 200s. Briefly, both models are presented here.

2 The Van der Put Model

The theory presented has, as its starting point,

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the idea that wood can be regarded as an isotropic material with uni-directional reinforcement. This, however, does not contribute to perpendicular and shear deformation. Initially, Van der Put applied his model to explain the embedment capacity of dowel-type fasteners in particle board. Later, it was used to determine the bearing capacity of continuous supported timber beams, Figure 2. The slope of the spreading stresses depends on the deformation considered. Assuming coniferous wood species and a 3% to 4% deformation, the slope is 1:1 and for 10% deformation 1:1.5. For a practical situation,

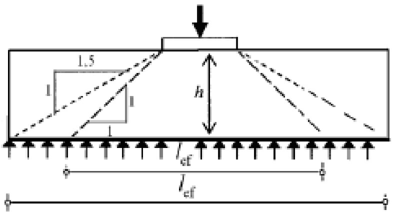

Figure 2. Continuous supported top loaded beam.

In which the loaded area is equal to the beam width, the stress dispersion model reads:

$$\frac{F_d}{bl} \leq \sqrt{\frac{l_{ef}}{l}} f_{c,90} = k_{c,90}\, f_{c,90} \qquad (1)$$

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} is the effective stress dispersion length at the support in grain direction in mm

$f_{c,90}$ is the standard compressive strength perpendicular to the grain in N/mm^2.

3 Eurocode 5 Model

The model of Eurocode 5: 2008 reads:

$$\frac{F_d}{bl_{ef}} \leq k_{c,90}\, f_{c,90} \qquad (2)$$

F_d the load in Newton

b the width of the beam in mm

l_{ef} is the effective length of the loaded area in grain direction in mm

$f_{c,90}$ is the standard compressive strength perpendicular to the grain in N/mm^2.

The effective length takes into account the contribution by the chord effect of nearby bended fibers and is estimated as the loaded length plus 30mm on each side. Values for the $k_{c,90}$ factors are given, depending on the support conditions. For continuous supports: $k_{c,90}$ = 1.25 solid softwood timber $k_{c,90}$ =1.5 for glued laminated softwood timber.

At discrete supports: $k_{c,90}$ = 1.5 solid softwood timber $k_{c,90}$ =1.75 for glued laminated softwood timber. For all other cases $k_{c,90}$ = 1.0. This last statement implies that for all wood species not being softwood, such as poplar, $k_{c,90}$ = 1.0. This obviously results for many hardwoods in conservative values. To show the influence of the choice of $k_{c,90}$ poplar is considered as softwood with appropriate $k_{c,90}$ values as well as being a deciduous wood species with $k_{c,90}$ =1.0. so two evaluations will be presented using the Eurocode 5 model.

4 The Experiments

The wood species used was Dutch poplar with a mean density of 412 kg/m^3 and a standard deviation of 48 kg/m^2. Equilibrium moisture content was attained for 20^{0}C and 60% RH. The experimental program was divided into the determination of the standard compressive

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strength, and the strength capacity of a number of different load configurations. The standard compressive strength is determined using a test specimen given in Figure 2, in accordance with EN408. It is fully supported and loaded over the complete upper surface. The specimen dimensions are 45x70x90 (*bxlxh*) with *h* as the perpendicular to grain direction of 90mm. Actual dimensions are given in Table 1. To evaluate the compressive capacity with the model predictions, Test Series A to D have been designed, Figure 3. Each Test Series contains specimens with depth of 45mm, 80mm and 150mm. Figure 3 shows only the 45mm depth specimens of Test Series B. Practical loading and support conditions were chosen as shown, ranging from beams that are fully supported, opposite loaded, adjacent loads, end loaded and end supported.

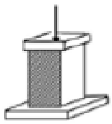

Figure 2. Compression specimen of EN408.

More details are given in Table 2. The load was applied to the specimens using steel plates with constant length and thickness but always covered the full width of the specimen. The same applies for the supporting or bearing steel plates. Harding A. [8] found no difference in the compressive strength after using steel plates with rounded or razor sharp edges

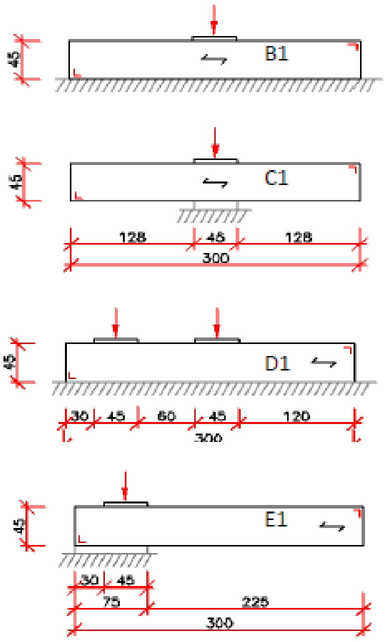

Figure 3. Specimens Series of 45mm thickness.

perpendicular to grain for Spruce. This is in contrast to the reasoning by Madsen [5] and Görlacher and Blass [6] assuming an effective contribution by deformed fibers.

Table 1. Specimen dimensions for the EN 408 compression test.

Replicates	Depth	Width	length	
18	90	45	70	[mm]
25	80	45	70	[mm]

The standard compressive strength, according to EN408, was determined by the intersection of a

Table 2. Specimen dimensions for the test Series B to E.

Replicates	Depth	Width	length	

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Deformation controlled				
3x6	45	150	300	[mm]
3x6	80	45	325	[mm]
3x6	150	45	535	[mm]
3x6	150	45	595	[mm]
Load controlled				
3x6	45	150	300	[mm]
3x6	80	45	595	[mm]

line parallel with the elastic part of the stress-strain curve and off-set 1%, figure 4. In the same way the compression strength capacity of all other specimens was determined using this 1% off-set method. In addition the compressive stress at 10% deformation was recorded.

3 Test Results

The mean and standard deviation of the standard strength and the specimen density according to EN408 are given in Table 3. The determination of the mean standard strength is very important as it is a material input variable for the models mentioned ($f_{c,90}$).

Turning to the other test results, the first data evaluation was performed to check for significant differences caused by the way of loading. For this purpose, the statistical T test for equal means was used. In general, it could be concluded that, for the data available, the method of loading did not significantly affect the results. This is quite an important result as load controlled tests take about 250-350s while deformation (displacement) controlled tests take 750 – 1500s.

In Table 4 the mean compressive strength values are shown; column (1) the load and support condition of the specimens, (2) the specimen depth, (3) the strength determined according to the method of figure 4 and in (4) the strength at 10% deformation.

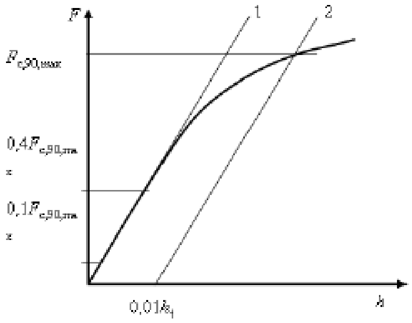

Figure 4. The compressive strength definition.

Table 3. Standard compressive strength.

Standard compressive strength (EN408)	
Number of tests	43
Average Density (ρ)	412 kg/m^3
St. Deviation Density	48
Strength	
Average $f_{c,90}$	3,70 N/mm^2
St. Deviation $f_{c,90}$	0,56

The differences in column (3), between the test series, are rather small but the differences are substantially higher for deformations of 10% This can be regarded as an ultimate limit state.

4 Model Evaluation

Four evaluations have been performed. Two Eurocode 5 predictions based on two choices for $k_{c,90}$, figures 5 and 6, and the Van der Put model for small and 10%. deformation, figures 7 and 8.

Table 4. Overview of mean test results

(1)	(2)	(3)	(4)

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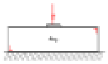
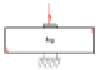
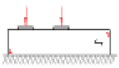
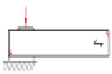
Series B	Depth	$f_{c.90}$	$f_{c.90.\,10\%}$
	45mm 80mm 150mm	6.62 7.04 8.02	9.83 13.08 15.34
Series C			
	45mm 80mm 150mm	5.68 5.07 5.60	7.08 8.04 10.19
Series D			
	45mm 80mm 150mm	5.77 5.82 6.64	8.45 9.33 9.82
Series E			
	45mm 80mm 150mm	5.47 5.11 5.65	7.27 7.70 9.56

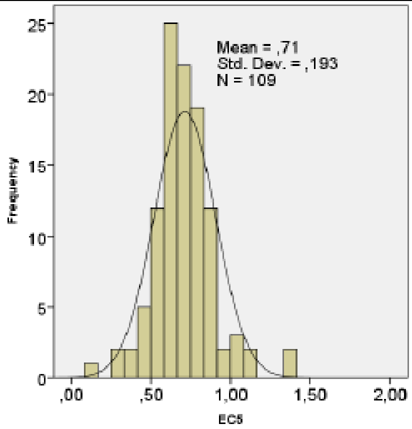


Figure 5. Test data ratio with EC5 model prediction with $k_{c,90}$=1.0.

For all test data the ratio between the actual observed test results versus the model prediction was determined. Figures 5 to 8 present this ratio as a histogram and a curved line representing a fitted normal distribution. Ideally the top of the curve should be at a ratio of 1.0. However, for both Eurocode predictions this situation is way off. As shown in Figures 5 and 6 the predictions exceed the experimental results with mean ratio values of 0.71 and 0.61 as indicated. Whether poplar is considered as softwood or not has only a marginal effect. In contrast are the results by the Van der Put model as shown in the Figures 7 and 8. For small deformations of about 4 to 5% the mean of the fitted normal distribution is 0.91and for 10% deformation. The ratio is 1.27. However the scatter in the ratio values, represented by the standard deviation, is smaller for the Eurocode 5 model than the Van der Put model, 1.93, 1.74 and 0.229 and 0.258, respectively.

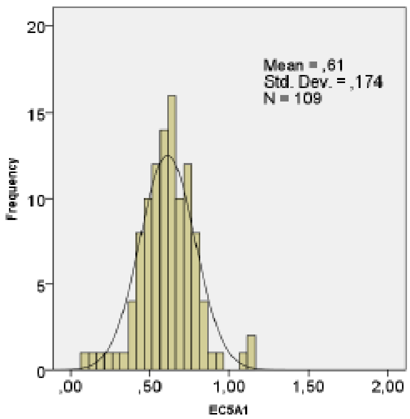


Figure 6. Test data ratio with EC5 model prediction with $k_{c,90}$ for softwood.

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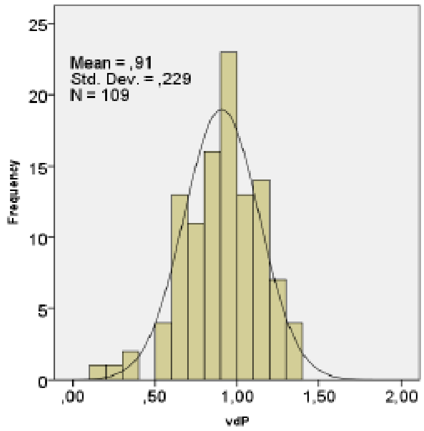

Figure 7. Test data ratio with Van der Put model for small deformations.

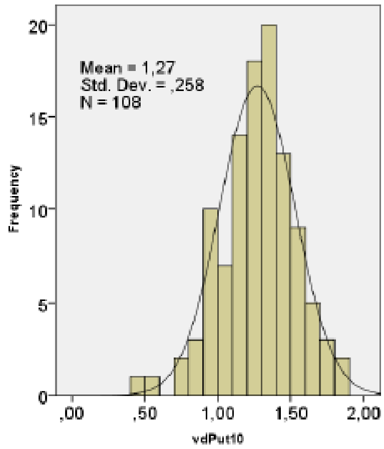

Figure 8. Test data ratio with Van der Put model for 10% deformation.

5.0 Conclusions

Based on 109 tests on Dutch poplar, it can be concluded that there is no significant difference between deformation control and load control tests.

Of the four models evaluated, the Eurocode 5 always predicts compressive strength values that are far too high resulting in non-conservative design. The results obtained with the Van der Put model are much more realistic and reliable.

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