The bearing strength capacity prediction by Eurocode 5 and other potential design code models

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THE BEARING STRENGTH CAPACITY PREDICTION BY EUROCODE 5 AND OTHER POTENTIAL DESIGN CODE MODELS

Adrian J.M. Leijten

ABSTRACT: In many timber structures the bearing strength and stiffness are issues to be considered by the design engineer. The linear elastic-plastic behaviour of structural timber loaded perpendicular to grain has been a problematic issue for decades which is reflected in the differences between the more than twelve published models in structural design codes over the world. This study considers the bearing strength of Spruce being the most common used structural wood species in Europe. On the bases of a large database of over 1000 test results covering seven load cases, three of the latest's bearing models including the one now present in Eurocode 5 are evaluated for their strength predictive ability. It is shown that none of the present design models accurately reflect reality apart from one model that is based on the yield slip-line theory.

KEYWORDS: timber, spruce, strength, compression perpendicular to grain, Eurocode 5.

1 INTRODUCTION

It is a known fact that the bearing strength capacity models in structural design codes mainly used around the world differ too much to accurately reflect the behavior of structural timber for all its practical applications, Leijten [1]. This study strives to end this situation for at least one wood species, Spruce (Picea Abies). A relatively easy way out for design code regulations is to prescribe calculation methods resulting in conservative predictions. Usually, an important input parameter for the models prescribed in the design codes is the standard Compression Perpendicular to Grain (CPG) strength. The lack of a unified approach to determine the standard CPG strength has led to situations where models and design equations are incomparable. The lack of a unified approach to determine the CPG strength has led to situations like in the Scandinavian countries. In these European countries, the standard characteristic bearing strength is 2-3 times higher than the stress at proportional limit determined by tests. This is considered questionable and far from conservative, Thelanderson and Mårtensson [2]. Also Kevarinmäki [3] concludes that the short-term CPG strength value for Spruce in Finland is too high, 6,5N/mm^2, and is associated with a deformation generally exceeding 10% of the timber member depth. He argues that 3,3N/mm^2 would be more appropriate. It will be shown that the reliability and accuracy of calculation models used for design is an issue to be considered. The evaluation presented below focuses on the reliability and predictability of three design models. Such undertaking requires a large database of experimental test results covering most of the design situations occurring in practice. In addition, all tests must have been carried out using the same test procedure and using the same method to determine and define the CPG strength.

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2 LOAD CASES

In order to support and distinguish the best predicting model, a sufficient number of test load cases should be evaluated. The load configurations should, to a large extent, reflect building practice situations. In Figure 1 an overview is presented of these

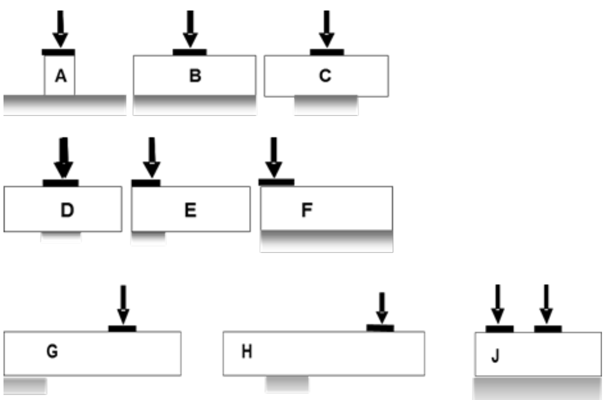

Figure 1: *Load cases considered*

load cases with A) standard specimen according to CEN/EN408 [4]; B) center load, full support; C & D) opposite load, local support; E) end load, local support;

F) end load, full support; G & H) discrete load; J) two spaced loads, full support. These categories were introduced in Leijten et al. [6] and incorporate fully and partially loaded cases. The arrow indicates the force applied, and a steel plate underneath takes care of uniform equal load introduction. The area with the highest CPG stress fails. In cases where the loaded area is as big as the support area, as in load cases D and E, both areas fail due to CPG simultaneously. Cases G and H are load cases without a direct support, so-called discrete supports, Load case H was later added by Lathuilliere [6]. Obviously one can vertically flip these load cases. It is assumed, however, that the timber at the load introduction fails in CPG. Load case J is added to check for the interaction between nearby loaded areas.

3 THE TEST DATA BASE

To enable comparison between the experimental test results carried out and reported by different researchers, all the experiments should use as a starting point a common standard test procedure and evaluation method to determine the CPG strength. The specimen used by the standard test method is shown in Figure 1 as load case A. This standardized specimen of clear wood is loaded over the full upper surface of 45x70mm with a depth of 90mm. The specimen depth equals the distance between the loaded surface and the bearing support. The deformation used for the load-deformation curves is the change of this distance. The latter is not fully in agreement with the test standard CEN/EN 408. However, Le Clevé [7] has shown that taking the deformation as the change in depth of the specimen is the preferred measuring method and provides more consistent results than using the CEN/EN 408 method, **Fehler! Verweisquelle konnte nicht gefunden werden.**. In this study, all evaluations were done by following the principles of CEN/EN408 but having a gauge length equal to the total specimen depth.

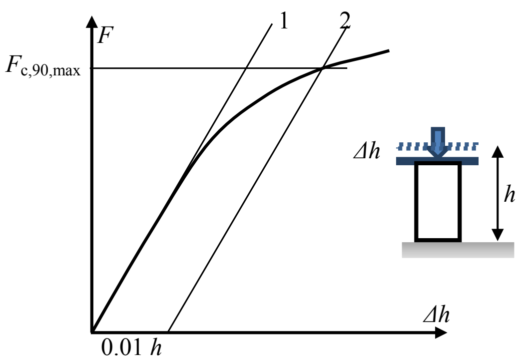

Figure 2: *Test method according to EN408[4]*

The CPG strength in CEN/EN408 is defined as the intersection of a line (2) parallel to the linear part of the load-displacement curve, line (1) that is off-set by 1% of the standardized specimen depth, Figure 2. In load cases B to G, where the test specimen dimensions deviate from the standard specimen, the same method is employed to determine the CPG strength. The deformations are plotted in [mm] and not in percentages of the specimen depth, the reason being that in the loading categories G and H it is not the whole specimen depth which is affected by the CPG stresses, Leijten et al. [8]. Furthermore, when the depth of the test specimen differs from the standard 90mm, the 1% off-set line (2) is off-set 1% of the actual specimen depth. Only for category D and E the 1% off-set refers to half the specimen depth. All the test data mentioned in this study used test specimens of European Spruce (Picea Abies) conditioned at 20± 2°C and 65±5% RH which results in an equilibrium moisture content of about 12%. The average standard CPG strength is found to be 3,15 N/mm^2, Table 1. Hoffmeyer et al.[19] reports tests on 74 sawn timber specimens and 120 glued laminated specimens having a mean CPG strength of 2,9 N/mm^2

Table 1*: Overview of standard CPG strength*

	Mean $f_{c,90}$	Specimen	Spruce
Source	[N/mm^2]	Number of tests	)[1]
Riberholt [9]	3,3	24	ST
Augustine et al.[10]	3,31	62	GLT
Poussa et al.[11]	2,80	200	ST
Hansen [12]	2,70	30	ST
Bleron et al.[13]	3,01	22	GLT
Hardeng [14]	3,69	8	GLT
Lathuilliere et al.[6]	3,26	42	GLT
Ed et al.[15]	3,12	6	ST
Lantinga et al. [16]	2,65	10	GLT
Goeij [17]	3,13	24	ST
Levé et al. [7]	2,51	48	ST
Mahangoe [18]	2,80	10	ST
Mean	2,81	342	ST
Mean	3,22	144	GLT
Overall mean	2,93	Total 487	

)[1] Type; ST=sawn timber; GLT=glued laminated timber

which corresponds with Table 1 overall average taking into account the number of ST and GLT specimens. Nevertheless their results are not included in Table 1 as they didn't perform the tests according to EN408 with the deviation mentioned under Load Cases. One of the conclusions in [19] was that the CPG strength does not change significantly with the specimen dimensions. This was later confirmed by Augustine et al. [10] for glued laminated Spruce specimens of 300 and 600mm depth.

4 DESIGN MODELS

For structural calculations the design engineer needs specifications how to determine the CPG lower 5% strength capacity. An overview of the models used by the building design codes in the last decades show an abundance of methods indicating a difficult to tackle problem. To mention a few models in the design codes, CIB Structural timber design code, 1983, NDS2015, AS1720, NZS3603, DIN1052, EN1995-1-1. Most of the strength capacity models are empirical in nature and are very simple. Models that were published after 1983 usually followed Eq.(1) as starting point.

$$\boldsymbol{\sigma_{c,90} = \frac{F_{c,90}}{b \cdot l} \leq k_{c,90} \cdot f_{c,90}} \qquad (1)$$

where: $\sigma_{c,90}$ is the actual CPG stress based on the load $F_{c,90}$ divided by the loaded surface area (b is the width and l is the parallel to grain loaded length); $k_{c,90}$ is a parameter that accounts for influencing factors like, moisture content, wood species, and load case; $f_{c,90}$ is the standard CPG strength value.

The design model now in use in Eurocode 5 is based on research by Madsen [20] and later modified by Görlacher and Blass [21], presented in Equation (2) with

$$\sigma_{c,90} = \frac{F_{c,90}}{b \cdot l} \leq \frac{l_{ef}}{l} k_{c,90} \cdot f_{c,90} \qquad (1)$$

$k_{c,90}$ values given in Table 2. The background for the introduction of an effective length, l_{ef} instead of the actual loaded length l is to account for the contribution by the rope effect of wood fibers adjacent to the loaded area. This rope effect proposed by Görlacher and Blass

Table 2: *$k_{c,90}$ according to Eurocode 5 [22]*

			$l_1 \geq 2h$	
		ST	GLT	
	$l_1 < 2h$		$l \leq 400mm$	$l_1 > 400mm$
LS	1	1,25	1,5	1
CS	1	1,5	1,75	1

LS=local support; CS=continuous support; ST=structural timber; GLT=glued laminated timber.

as determined with Madsen's test is 30mm at maximum. The nature of the tabulated $k_{c,90}$ values result in unrealistic jumps in the design capacity. Especially if the loaded length of a support is close or slightly more than 400mm, the $k_{c,90}$ value drops from 1,75 to 1,0 applicable to glued laminated beams. The background for these jumps is unknown.

The only design model based on a physical theory is presented by Van der Put in 1990 [23] and is found to have a high potential [24]. The model is based on the assumption that the compressive stresses spread as in an isotropic material as if the effect of the relative stiff fibers parallel to grain can be ignored. These stresses distribute over the depth of the material according to the yield or slip line theory. The degree of spreading depends on the deformation as shown in Figure 3. From theoretical considerations it follows that at the onset of yielding the compressive stresses spread by 1: 1 (45^0 degrees) and for large deformations of about 10% the spreading angle is 1:1,5 (34^0 degrees). This is in agreement with findings by [25] who in 1982 reported

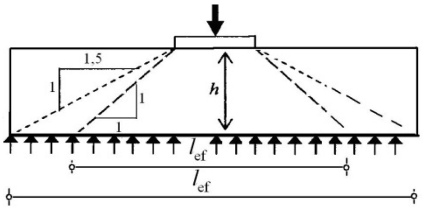

Figure 3: *Assumed spreading of compression stresses*

The same spreading ratio for CPG stresses to die out. The theory applies generally and therefore is assumed to be wood species independent. The model is given by Equation (3).

$$\sigma_{c,90} = \frac{F_{c,90}}{b \cdot l} \leq k_{c,90} \cdot f_{c,90} \rightarrow k_{c,90} = k\sqrt{\frac{l_{ef}}{l}} \qquad (3)$$

were l_{ef} is the effective or spreading length parallel to the grain as shown in Figure 3; k is a correlation factor to cater for differences in model prediction and experimental results. Although it is suggested in v.d.Put [26] that for load case B theoretically this k-factor is approximately 1,1 for all other cases the suggestion is k=1,0. The effective length is restricted by the geometric (dimensional) boundaries of the beam or by nearby spreading stresses, Figure 4. For situations where the

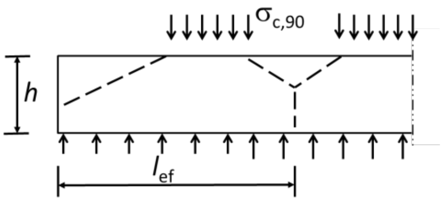

Figure 4: *Restrictions for the effective length*

support conditions are not continuous but discrete as in load cases G and H, Figure 1, previous models did not provide any guidance for the design engineer. In Leijten et al. [27] it was shown that for load cases G and H the depth of the spreading stresses is limited to a maximum of 140mm or 40% of the beam depth, whichever is the smallest, Equation (4)

$$k_{c,90} = min\begin{cases} 140mm \\ 0,4h \end{cases} \qquad (4)$$

where h is in mm. The last and most recently published model by Lathuilliere et al. [6] is actually a semi-empirical model. Although the derivation initially follows analytical principals, the introduction of arbitrarily fixed values for certain parameters brings it down to a fitting procedure. The model is presented as:

$$\sigma_{c,90} = \frac{F_{c,90}}{b \cdot l} \leq k_{c,90} \cdot f_{c,90} \qquad (5)$$

where:

$$k_{c,90} = 1 + \frac{f_v}{f_{c,90}} \cdot \frac{k_{sh} \cdot h_t}{l} \cdot \frac{2}{3} \cdot k_{sb} . k_{sc} \cdot n_d \qquad (6)$$

with:

$$k_{sh} = \begin{cases} \frac{1}{3} \; in\ case\ of\ bending \\ \frac{1}{2} for\ all\ other\ load\ cases \end{cases}$$

(in [6] the values are reversed accidently)

$$k_{sb} = b^{-0.325}$$

$$k_{sc} = \begin{cases} 1.51 \; descrete \; support \\ 1.85 \; continuous \; support \end{cases}$$

$$n_d = \begin{cases} 1 \quad end \; support \\ 2 \; for \; intermediate \; support \end{cases}$$

where f_v the shear strength; $f_{c,90}$ the standard CPG strength; h_t the beam depth; l the length parallel to grain of the loaded area; b width of the loaded area

5 THE TEST DATA BASE

A literature search results in many reports dealing with CPG. Besides strength and stiffness data, there is also information about factors that influence these properties. These are the wood species, load case, moisture content, specimen shape, annual ring orientation, etc. All of these have drawn attention and have been investigated. They form a value source of information however most tests have not been performed according a common method nor is the CPG strength defined in the same way. For this reason most of the older even pre-WWII tests had to be ignored. The remainder consists of test data taken from fourteen literature sources [6-18, 28]. The test specimens varied in dimensions as to cover what can be expected in building practice from a loaded length (parallel to grain dimension) of 40 to240mm, a loaded width (specimen width) from 40 to 210mm and a specimen depth from 40 to 600mm. More detailed information about the dimensions of the test specimens is given in Leijten [29]. On the load-deformation curve of each test two points are of interest. The first value related to the onset of yielding determined with the off-set line as shown in Figure 1 and the second the CPG stress at 10% deformation. The total number of test samples is 104 with 1017 test results in total for the on-set of yielding deformation and 59 samples with 524 test results for 10% deformation. The number of samples are very unevenly distributed over the load cases. For instance, for the on-set of yielding, 39 samples with 332 test results (one third of the total) deal with load case B while a few tests have been reported for load case C.

Table 3: *Overview of samples and test data per load case*

load cases	onset of yielding n samples	Number of tests #	10% deformation n samples	Number of tests #
B	39	332	30	220
C	4	4	0	0
D	15	153	2	37
E	3	51	1	14
F	14	240	6	70
G	21	180	17	153
H	8	30	0	0
J	3	30	3	30
Total	104	1020	59	524

Table 3 shows the number of samples as well as the total number of test results per load case. For the two load cases G and H, the distance between the support and the load is at least 2,5 the specimen depth. Not all the sources allowed the assessment of the CPG stresses at 10% deformation and for that reason the number of test results in the last column of Table 3 are different from the third column. Again, load case B is studied most at 10% deformation having still 30 test samples with 220 test results (42% of a total of 524).

6 EVALUATION OF MODELS

Although statistical analyses deliver values for key parameter to quantify differences between models, a graphical representation is added to show what statistical values leave to imagine. The figures that follow show the model prediction of the three models mentioned above versus the test samples mean results being the models by Van der Put, Eurocode 5 and Lathuilliere, respectively.

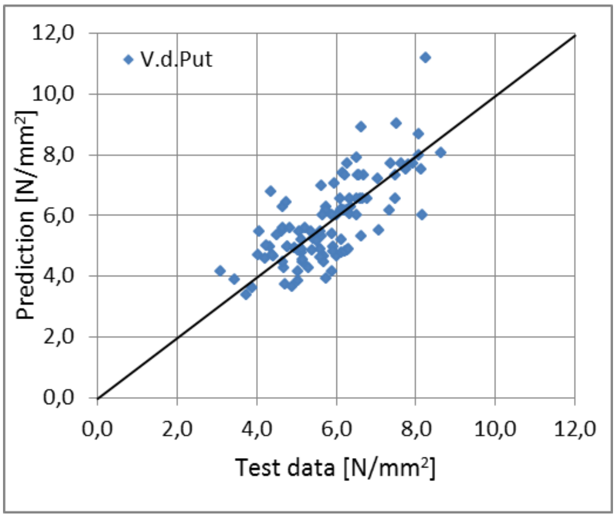

Figure 5: *Test results versus Van de Put model prediction..*

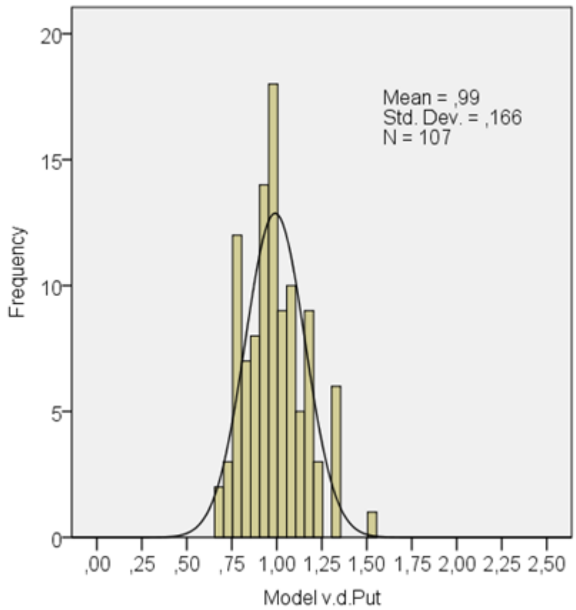

Figure 6: *Histogram of the Van de Put model prediction amd test results ratio.*

These figures are complimented with a histogram of the ratio values of the model prediction and test sample mean value with appropriate mean and standard deviation. In addition a fitted normal distribution curve is presented.

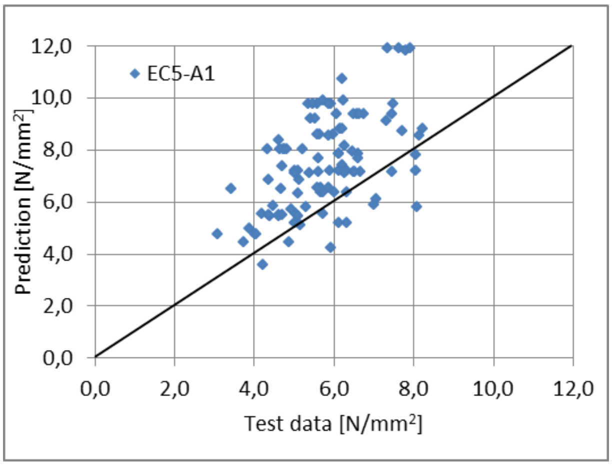

Figure 7: *Test results versus the Eurocode 5/A1 model prediction.*

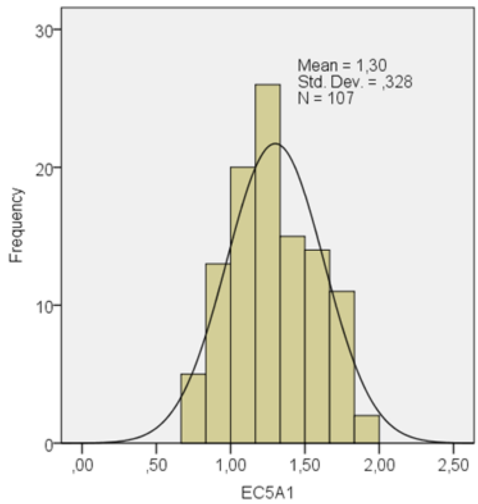

Figure 8: *Histogram of the Eurocode 5 model prediction and the test results and ratio.*

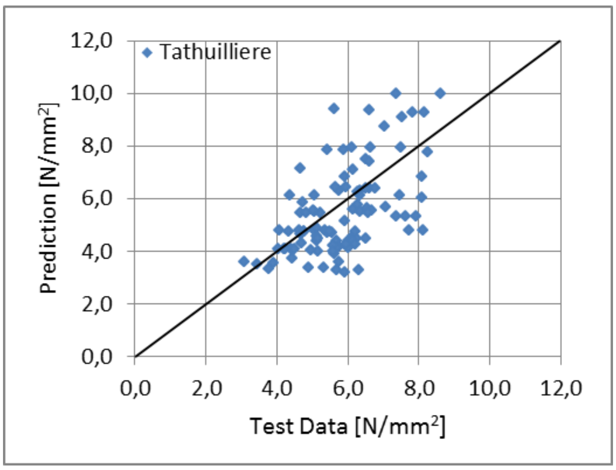

Figure 9: *Test results versus the Lathuilliere model prediction*

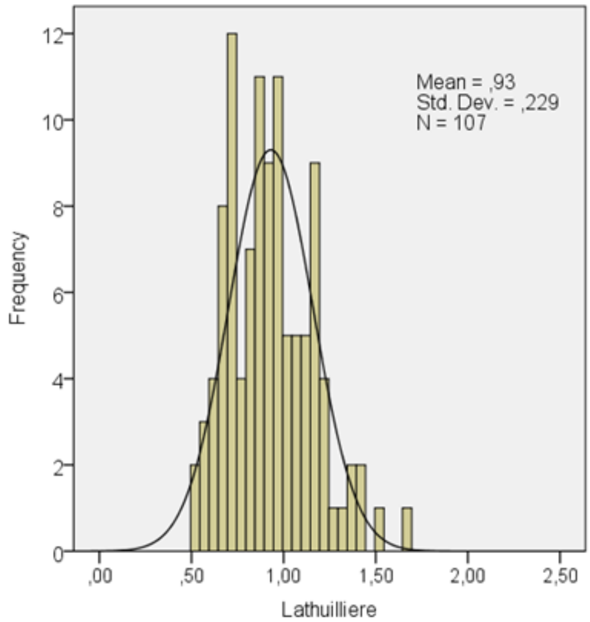

Figure 10: *Histogram of the Lathuilliere model prediction and the test results ratio.*

In Table 4 an overview is given about the statistical mean and standard deviation of the fitted normal distributions of the histograms for the on-set of yielding as well as for 10% deformation, although the graphs of the histograms of the latter are not presented here.

Table 4: *Overview of the statistical parameters of the histograms of Figures 6, 8 and 10.*

Model	On-set of yielding		10% deformation	
	Mean	Stand. dev	Mean	Stand. dev
Van der Put	0,99	0,166	0,83	0,132
Lathuilliere	0,93	0,229	0,65	0,170
EC5-A1	1,30	0,328	0,99	0,237

In the analysis above all test data has been considered irrespective of the load case, Figure 1. To check if the models perform differently per load case and deformation, the same evaluation is repeated but for each load case separately, Table 5. From this Table it follows that again the Van der Put model is the most consistent for the onset of deformation. The frequently in building practice occurring load case B is on average +10% to low. This is in contrast to the Lathuilliere and EC5/A1 model in which predictions are respectively +9% and +37% too high. Even for load cases H and J the EC5/A1 model is out by more than +30%. An effort was made to improve the performance of the Van der Put model by making use of the parameter k in Equation (3) and the deviations from the ideal ratio of 1 to apply a $k = 0{,}9$ for load case B and $k = 1{,}15$ for load cases C, H and J for instance. However, this didn't significantly improve the overall performance of the model nor did the standard deviation decrease much.

Table 5: *Overview of model performance per load case.*

Load case	Samples #	Tests n	Mean prediction / test result		
			V d Put	Lathuilliere	EC5/A1
			Onset of yielding		
B	39	329	1,09	0,90	1,37
C	4	4	0,88	0,65	0,83
D	15	153	0,97	0,89	1,16
E	3	51	0,97	0,86	1,23
F	14	240	0,92	0,81	1,18
G	21	180	0,99	1,13	1,39
H	8	30	0,89	1,14	1,32
J	3	30	0,85	0,73	1,14
mean			0,96	0,91	1,21
St, dev			0,08	0,17	0,18
Var.co.			8%	19%	15%
Total	104	1017			
			10% deformation		
B	30	220	0,81	0,59	0,93
C	0	0			
D	2	37	0,88	0,66	1,21
E	1	14	0,94	0,76	0,98
F	6	70	0,87	0,63	1,01
G	17	153	0,91	0,83	1,07
H	0	0			
J	3	30	0,85	0,69	1,14
mean			0,88	0,70	1,06
St. dev			0,04	0,09	0,10
Var.co.			8%	13%	9%
Total	59	524			

The Eurocode 5 model currently in use by building practice is the not best performing. The main cause of this is the inability to account for the differences in the depth of the beam and the jumps in the $k_{c,90}$ values, Table 2. At 10% deformation, the CPG strength increases by about 15% as compared to the onset of yielding. Since neither the EC5 model nor the model of Lathuilliere take into account the level of deformation, these models automatically give a lower ratio values. Furthermore, since the EC5 model substantially overestimates the CPG strength at 1% deformation, by change it gives a good prediction at 10% deformation. In contrast the Van der Put model is the only model that acknowledges the increased CPG strength at 10% deformation; although apparently not to the extent of the test results, Table 5. Nevertheless being the only of the three models accounting for this increase, the Van der Put model is the most appealing.

There are obviously many more variables to check with the models. One of them is the length of the loaded area or the (effective) depth of the test specimen versus the strength prediction/test data ratio. In particular the (effective) depth might be of interest as for instance a 10% deformation of a 40 mm depth specimen is very different from a 400 mm specimen. How the models cope for the onset of yielding deformation with these differences is presented for all load cases and for load case B as the most frequently tested, in Figure 11 and 12, respectively. In both figures the EC5/A1 model tend to be well represented in the non-conservative part (>1,0). On average in both figures the EC5/A1 model results in a non-conservative approach.

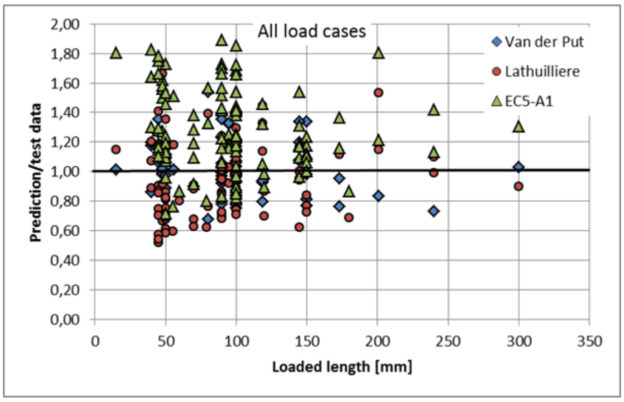

Figure 11: *Model prediction ability versus loaded length*

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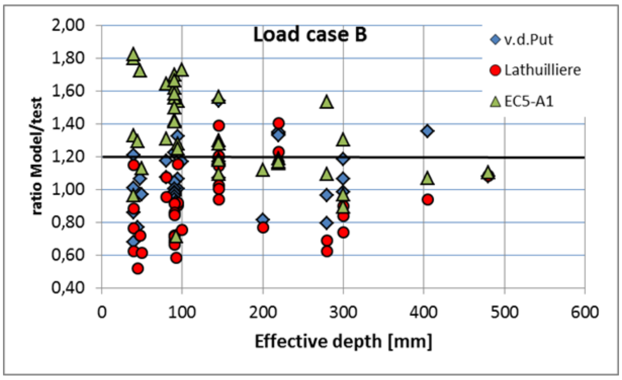

Figure 12: *Model prediction ability versus the (effective) depth.*

7 PRACTICAL ISSUES

Code writers can sometimes be confronted with conflicting situations when current practice allows higher values than new proposed and scientific validated models predict. Specifically in the Scandinavian countries design compressive strength values are very high as mentioned in the introduction. Adoption of the best design model presented in this study by the new Eurocode 5 (2020) would bring the design values down. The fact that the current design model in Eurocode 5 didn't result in failures is probably caused by the fact that overload situations hardly ever occur. Confronted with this situation the Eurocode 5: 2004 specified an option to increase the design capacity if the deformation up to 10% would not impair the structural safety of the timber structure. The model by van der Put considers this 10% deformation as an alternative limit state. Still the design values might be too low for the industries in the countries mentioned above. There are several options to even allow further increase of the design capacity. The characteristic compressive strength is multiplied by a k_{mod} accounting for load duration and moisture and divided by the partial material safety coefficient (γ=1,3). The latter is derived from situation where brittle failure is expected. Plastic failure modes like compression perpendicular to grain have in this respect not been considered. It seems reasonable to lower this coefficient. In the Eurocode committee a discussion to do so is imminent.

8 CONCLUSIONS

The main aim of this study is to give a state of the art of the available test data of compressive perpendicular to grain (CPG) strength for the wood species Spruce (Picea Abies) and to test the predictive ability of three models. Test data of a great number of sources is collected which all had a common test method and definition of the CPG strength. Eight load cases are distinguished and the predictive ability of three models is compared at the onset of yielding as well at 10% deformation. The three models selected are the latest published empirical, semi-empirical and physical models as given by the Eurocode 5/A1 [22], Lathuilliere et al. [6] and Van der Put [26], respectively. Considering all eight load cases it can be concluded that the best and most consistent and accurate model is the physical Van der Put model [26]. Compared to the Eurocode 5/A1 model it requires hardly more calculation effort. The Eurocode 5/A1 model currently applied by practice is the least of the three models evaluated.

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