Eurocode 5 design in comparison with fire resistance tests of unprotected timber beams

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INTRODUCTION

It is generally recognized that heavy timber in fire conditions demonstrates high structural performance. Exposed timber chars which functions as an isolative layer which protects the inner material from heat and loss of load bearing capacity. Char has no significant strength, and therefore, as the char layer grows, the load bearing capacity of the timber member reduces under sustained fire conditions. For predictions of the load bearing capacity in a standard fire, Eurocode 5 (EN 1995-1-2, 2012) provides a reduced cross-section method (RCSM), in which a char layer and an additional zero strength layer are simply deducted from the cross-section for structural calculations. Furthermore, using the RCSM, the design strength of timber under fire conditions is assumed to be higher than that under ambient conditions.

Recent discussions regarding RCSM concern the size of the zero strength layer (Schmid et al., 2014), the assumed change of material strength in the fire situation and the suitability of the method for time to failure predictions that exceed 60 minutes. This paper evaluates the RCSM method by comparisons with experimental results of unprotected beams loaded in bending under standard fire conditions.

REDUCED CROSS-SECTION METHOD

The reduced cross-section method, sometimes called Effective Cross-Section Method, can be used to determine the *structural fire resistance*, which is the time to failure in a standard fire, of timber beams, columns as well as floor- and wall- assemblies. Using the reduced cross section method, an effective cross-section is determined by subtracting a charring layer and a zero strength layer, as shown in Figure 1. The charred material is, hereby, disregarded as it has no significant strength. The zero strength layer is taken into account in order to compensate for losses in strength and stiffness of the uncharred timber beyond the char layer.

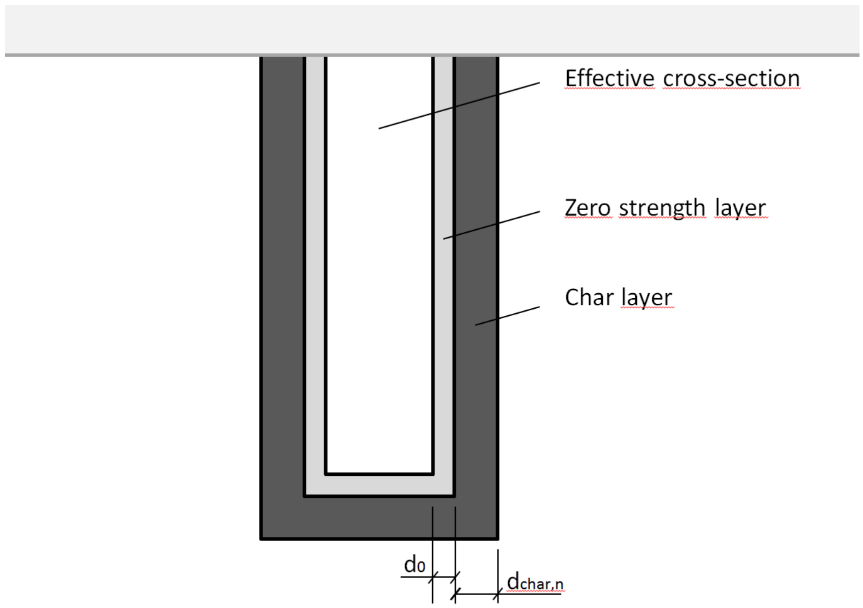

Figure 1: Effective cross section of a beam in accordance with the reduced cross-section method

The zero strength layer

Schaffer (1986) determined that the zero strength layer, d_0, should be 0,3 inch which is approximately 7,6 mm. He achieved this number by averaging an estimated strength and Young's modulus of timber in the heated zone, which was defined as the timber layer of 40 mm beyond the char line. Schaffer stated that he used a transformed section analysis to calculate the strength of the beam. This type of analysis is generally used to determine the bending capacity of composites comprising two or more materials with different Young's moduli. In Schaffer's work the outer 40 mm were considered to have the reduced average tensile strength and modulus of elasticity. The predicted bending capacity corresponding to this transformed section analysis was similar to the capacity of a beam with a reduced cross section. The reduction of the geometry necessary to account for this decrease of load-bearing capacity was 0,3 inch of uncharred material on each exposed side(s).

The zero strength layer, d_0, according to Eurocode 5 is based on Schaffer's work and is 7 mm for fire durations of more than 20 minutes. However, it should be noted that Schaffer applied a simplification, which may be significant, by averaging material properties of the outer 40 mm of the uncharred timber section.

5^{th} percentile strength in the fire situation

Norén (1988) presented results of 74 model scale fire tests of beams and an equal amount of reference tests at ambient temperature to predict the strength of the source material. Timber was cut through the pitch to obtain two specimens with equal knot sizes and of equal density, which could be used for the fire test and a corresponding reference test. The cross section of the beams was 45 x 120 mm and the average fire resistance was 14,7 minutes for loads of one-sixth of the maximum capacity and 9,7 minutes for loads of one-third of the maximum capacity. The study showed that the standard deviation of load-bearing capacity under fire conditions was lower than that at ambient temperatures. It was concluded that the strength is higher in the fire situation.

The above described behavior (reduction of the scatter of effective strength properties) can be described introducing a factor, k_{mod}. It was found, that this factor leads to the shift of the 5th percentile value for fire conditions so that it resembles the 20th percentile value for ambient conditions. Further, when drafting the first version of Eurocode 5, the mandate decided that the introduction of the new design concept (semi-probabilistic design) and calculation procedures were not allowed to increase or a decrease of national safety levels. It was found, that the introduction of k_{mod} was appropriate to avoid the increase of cross-sections typically used for timber design in Europe.

The use of the 20th percentile strength for the fire design was introduced in Eurocode 5. However, recently the use of the 20th percentile strength value has been questioned as it originates from tests of relatively slender beams with a relatively low fire resistance. The use of the 20th percentile strength layer for larger beam cross-sections should be justified. For other materials corresponding rules do not exist.

EXPERIMENTAL STUDIES

A study by Schmid et al. (2014) reviewed fire tests of timber beams in furnaces. Their study showed that most test results found in literature were considered to be questionable, due to e.g. the absence of actual strength properties of the timber tested. This paper considers a number of comparative analyses between the predictions in accordance with the RCSM of Eurocode 5 and available test results from the literature.

COMPARATIVE ANALYSES

The predictions according to the RCSM of the Eurocode 5 aim to predict the 5th percentile fire resistance rating, for timber of a specified strength grade. In order to compare the 5th percentile fire resistance rating of experiments with the predicted 5th percentile fire resistance rating, statistical analysis would be required. For this type of analysis the sample size (number of tests) should be large enough. The test results should represent an appropriate number of timber beams from a suitable number of timber producers and graders, so that the distribution of beam properties resembles the distribution of properties of all timber within the timber grade under investigation.

The use of the 20th percentile strength to predict the 5th percentile fire resistance could be validated statistically if approximately 95% of a suitable number of suitable beam tests is underestimated using the method. It also has to be assumed that there was no additional selection process performed after the grading prior to the test.

Comparison 1a: test results versus predictions according to Eurocode 5

In practice the fire resistance of a beam is calculated using the strength grade that is usually provided by the manufacturer. Some tests that were reported in the literature involved graded timber. Therefore, *Comparison 1* considers tests for which the timber grades were reported and corresponding predictions. 95% of the timber should have at least the characteristic strength corresponding to the strength grade. Similarly, regarding fire resistance, 95% of the tested beams should fail after the predicted time to failure (as the strength of timber is assumed to be homogeneous in accordance with Eurocode 5).

For Comparison 1 it has to be assumed that there was no selection of the material after the timber grading, and that the performers of the tests randomly picked there specimens from the timber of a specified timber grade.

Peter and Gockerl (2006), Lange *et al.* (2014), Wynistorf (2016) have performed standard fire tests of strength graded timber beams that were subjected to bending. Table 1 gives a summary of the parameters corresponding to these tests. Shear failure was indicated for two tests, which is considered out of the scope of this paper. Furthermore, the fire resistance, i.e. failure load and failure time, of five tests were missing. Therefore, the results of these fire tests could not be considered for analyses in this paper.

Table 1: Summary of test parameters (grey script indicates that the results were not further used)

Author	Grade	Width (mm)	Height (mm)	Density (kg/m3)	Moisture content (%)	Bending moment (kNm)	Sides of exposure	Load ratio	Fire resistance (min)
Wynistorf (2016)	GL24h	157	254	432,4	12,6	16,3	3	0,30	51,8
	GL36h	158	256	49,5	12	N.A.	3	0,30	N.A.
	GL36h	158	255	496,7	10,9	13,4	3	0,20	68,9
	GL24h	158	252	419,8	10,9	N.A.	3	0,30	48,1
	GL36h	157	253	513,3	10,7	21,1	3	0,30	58,3
	GL36h	157	217	463,6	N.A.	14,6	3	0,30	44,4
Peter and Gockerl (2006)	GL24h	120	362	474	12,4	23,0	4	0,23	48,2
	C24	139	278	475	22,2	16,5	4	0,28	51,5
	GL24h	140	600	463	11,3	97,0	4	0,30	32,0
	GL32h	140	599	408	10,7	124,5	4	0,27	24,5
	GL32h	140	600	460	10,7	124,5	4	0,27	13,5
Lange (2014)	L40c***	140	269	454	11,5	14,2	3	0,22	43,0
	L40c	140	269	451	11,8	14,2	3	0,22	>43
	L40c	140	269	462	11,7	23,5	3	0,37	22,0
	L40c	140	269	479	11,9	23,5	3	0,37	>22
	L40c	140	269	449	11,6	17,1	3	0,27	42,0
	L40c	140	269	439	12,3	17,1	3	0,27	>42
	L40c	140	269	469	11,5	10,2	3	0,16	61,0
	L40c	140	269	449	11,6	10,2	3	0,16	46,0

* Tests indicated shear failure

** The fire resistance or the applied load is unknown

*** L40c corresponds to a characteristic strength of 30,8 N/mm^2

The predicted fire resistance and the experimentally determined fire resistance can be compared using Figure 2 and Figure 3. Figure 3 includes the frequency of errors and a normal distribution based on the mean and the standard deviation of the sample. The error is in this paper defined as the difference between the experimentally determined fire resistance and the predicted fire resistance. To indicate the position that a similar distribution should have so that 95% of the predictions is overestimated, an expected normal distribution curve is shown. The red dashed curve represents zero error, which should in this case be at the 95% lower bound value of the normal distribution. Quite a significant change of the predicted results is required in order to correspond to the 95% confidence. It should be noted that the sample size is arguably not large enough consider a normal distribution. However, this is typical for fire resistance tests which are in general very costly.

Interpreting the results shown in Figure 3, it can be seen that the fire resistance of seven out of twelve beams was underestimated. Similarly five out of twelve beams were overestimated. The probability that at least seven out of twelve tested beams have strengths below the 5^{th} percentile strength is extremely small, approximately 1 in two-million. Therefore, it can be stated with practically 100% certainty that either the grading or the model causes a non-conservative error.

The grading of the specimens by Peter and Gockerl (2006) was performed according to EN 338. All lamellas of the beams that were reported by Wynistorf were grade using a Golden Eye 706 and a novel advanced method of predicting the strength properties (Fink, 2014). It is, therefore unlikely that the grading procedure causes the non-conservative error.

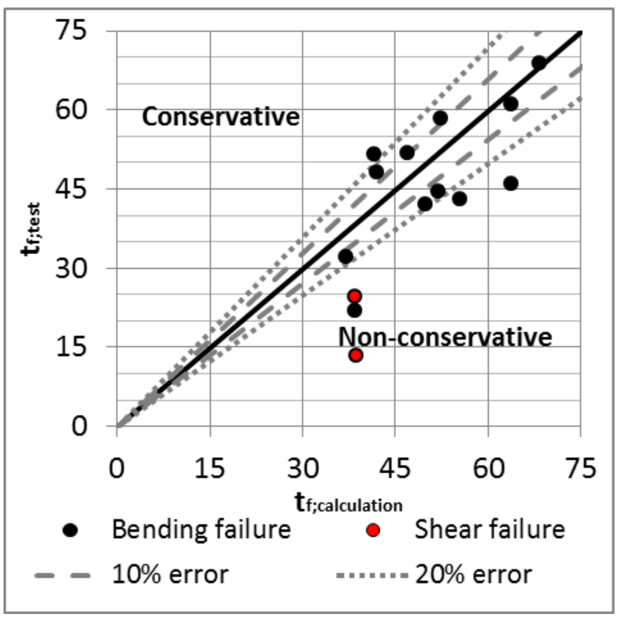

Figure 2: Test results versus predictions the fire resistance using Eurocode 5

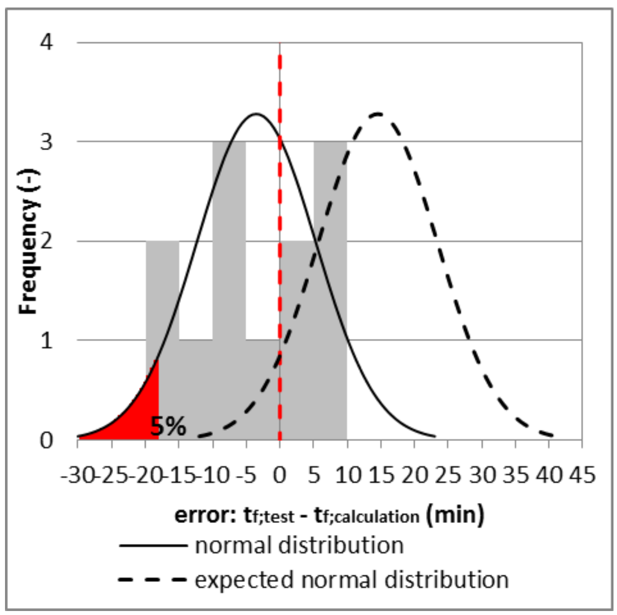

Figure 3: Frequency of errors, corresponding normal distribution and expected normal distribution using Eurocode 5 (bending failure only)

As mentioned before, the use of the 20^{th} percentile strength to predict the strength with a 95 percent confidence interval is currently questioned. The use of the 20^{th} percentile strength instead of the 5th percentile strength is in this paper challenged, by comparisons between results corresponding to the 5th and the 20th percentile strength.

Comparison 1b: test results versus predictions using the RCSM and the 5th percentile strength

Figure 4 shows predictions corresponding to the RCSM and the corresponding experimental results. Five out of twelve tests were overestimated, which could be accepted if these five beams had strengths below the 5th percentile strength. However, the probability that at least five out of twelve tested beams have strengths below the 5th percentile strength is approximately 0,0002%. It is, therefore, almost certain that either (1) the strength grading or (2) the use of the RCSM and the 5th percentile strength does not correspond to a confidence interval of 95%.

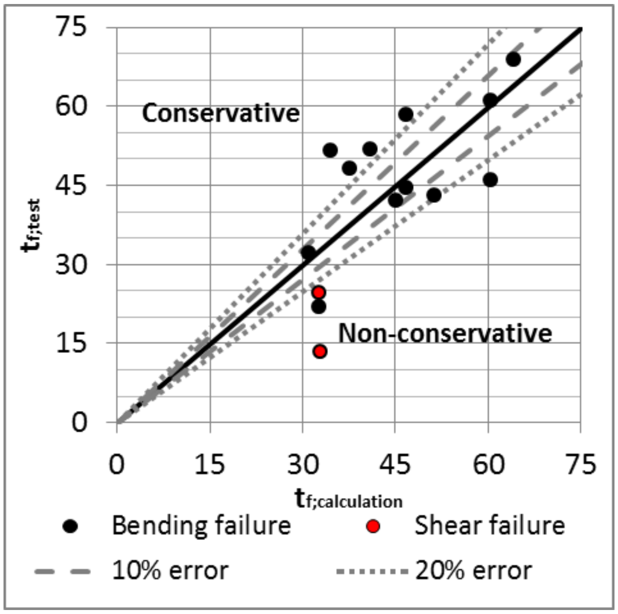

Figure 4: Test results versus predictions of the fire resistance using the **5th percentile strength**

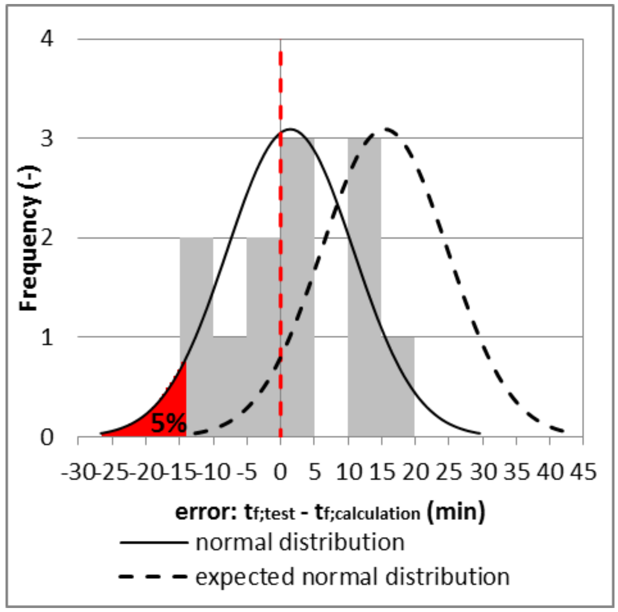

Figure 5: Frequency of errors and the corresponding normal distribution using the RCSM and the **5th percentile strength** (bending failure only)

Figure 5 shows the frequency of errors and the normal distribution based on the standard deviation and the mean of the sample. The resulting normal distribution is slightly more reasonable than the normal distribution obtained using the 20th percentile strength (Figure 3).

Comparison 1c: test results versus predictions using the RCSM, the 5th percentile strength and an increase zero strength layer

The zero strength layer has been questioned and it has been recommended to increase the size of the zero strength layer in multiple studies. In this analysis, the effect of a doubled thickness (14mm) of the zero strength layer is studied. The results for Comparison 1c are shown in Figure 6 and Figure 7. One of the twelve tests is overestimated when using the RCSM, the 5th percentile strength and a doubled zero strength layer of 14mm for durations exceeding 20 minutes. The probability that exactly one of twelve specimens is weaker than the 5th percentile strength is 34%, which is plausible. It is, therefore, plausible that the use of the RCSM, the 5th percentile strength and a zero strength layer of 14mm corresponds to a confidence interval of 95%.

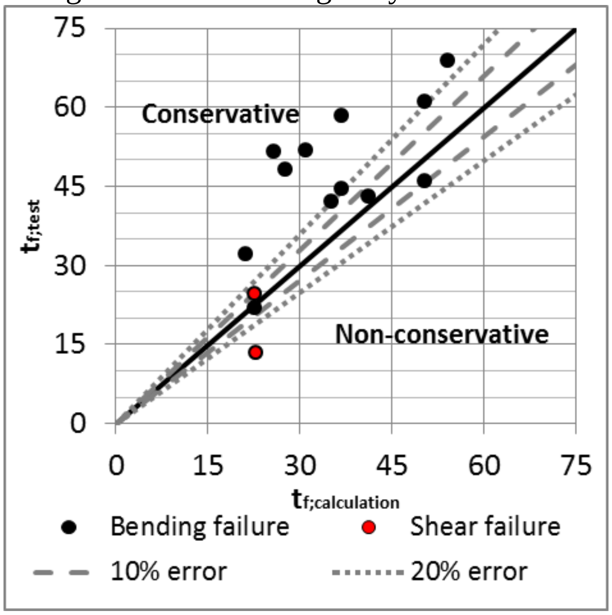

Figure 6: Test results versus predictions of the fire resistance using the **5th percentile strength** and a **doubled zero strength layer**

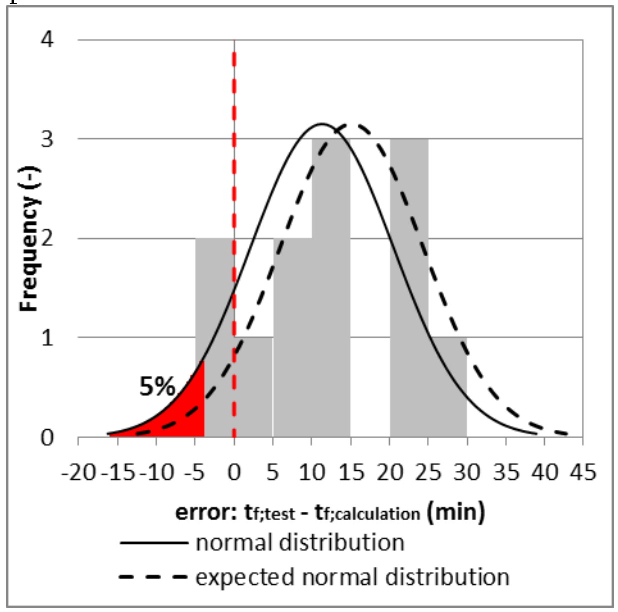

Figure 7: Frequency of errors and the corresponding normal distribution using the RCSM, the **5th percentile strength**, and a **doubled zero strength** layer (bending failure only)

Comparison 2: test results versus predictions using the RCSM and estimated strengths

In case the bending strength (at ambient temperature) of the beam is known, comparisons between test results and predictions could be used to validate the RCSM. However, as the beam cannot be damaged before the fire tests, the bending strength has to be determined in another way. The strength corresponding to most beam tests was already predicted by Schmid et al. (2014). The same methods are applied in the current work:

- Method A involves reference tests at ambient temperature. In order to estimate the strength of the fire tested specimens, specimens that resemble the fire tested specimens are loaded until failure occurs.

- Method B involves estimating the strength properties from the Young's modulus, by assuming the relationship given in the Probabilistic Model Code (JCSS) (see Figure 8).

- Method C involves estimating the strength properties from characteristic strength that corresponds to the strength grade. Ratios between the mean and the characteristic strength given in EN 1363-1(1999) are used for this study. Table 2 gives a short overview of these values.

- Method D involves estimating the strength properties from the density, by assuming the relationship given in the Probabilistic Model Code (JCSS) (see Figure 9).

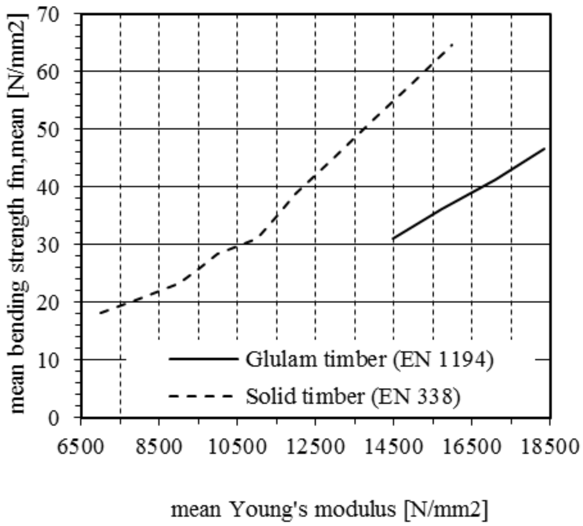

Figure 8: Relationship between the mean Young's modulus and the mean bending strength, according to the Probabilistic Model Code (JCSS, 2007)

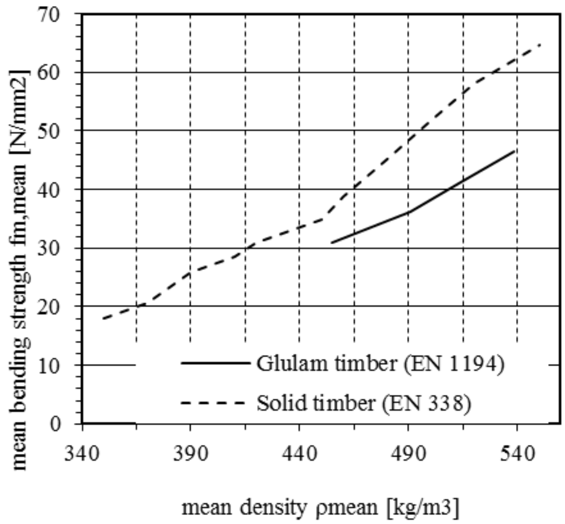

Figure 9: Relationship between the mean density and the mean bending strength, according to Probabilistic Model Code (JCSS, 2007)

Table 2: Ratio between mean and the 5th percentile value according to EN 1363-1(1999)

	Bending strength
Solid timber	1,55
Glued laminated timber	1,29

The experimentally determined fire resistance and predictions using the estimated strengths are shown in Figure 10. It can be seen that there is a reasonable correlation between the predictions and the test results, as the data points are relatively close to the diagonal line. This correlation is also visible in Figure 11, from which it can be seen that the mean error is nearly exactly equal to zero.

It should be noted that the calculations did not incorporate the use of the 20th percentile strength, as the strength was determined per specimen (or sample). Comparison two can, therefore not be used to validate the 20th percentile strength. However, it can be used to assess the thickness of the zero strength layer as it is incorporated in the RCSM. As the mean error is approximately zero, this analysis suggests that the zero strength layer is reasonable. It should, however, be stated that there are uncertainties that can be significant. Schmid et al. (2014) argued that testing procedures and the estimation of material properties, potentially, involve uncertainties.

The use of the RCSM to predict fire resistances exceeding 60 minutes is not allowed according to Eurocode 5. As there is a demand for calculation methods that can be used for higher fire resistances. In order to test the RCSM for fire resistances that exceed 60 minutes, Figure 12 and 13 include predicted fire resistances that are higher than 60 minutes. It can be seen that there was only one prediction exceeding 75 minutes. *Note: the following sentence is corrected after the conference:* Therefore, it is concluded that the reduced cross section method according to Eurocode 5 needs more data in order to be used for calculations of fire resistances exceeding 60 minutes.

Table 2: Method of strength prediction corresponding to the different publications

Author	Method of strength prediction	Reported Young's modulus (N/mm^2)	Reported density(kg/m^3)	No. of tests**
Dorn et al. (1967)	B	9700-11950	450-475	17
Hall (1968)	D	NA	NA	4
Dreyer (1969)	B	9000-17600	500-575	14
Dreyer (1970a)	C	NA	425-500	10
Dreyer (1970b)	C	NA	400-475	10
Peter (2006)	A	9680-13000	350-450	5
Lange (2014)	A	12600-13800	420-495	8
König et al.* (1997)	A	12900-14300	NA	4
Wynistorf* (2016)	A	10500-14500	420-510	6

* Model scale tests

** Only unprotected and untreated beams loaded in bending are counted

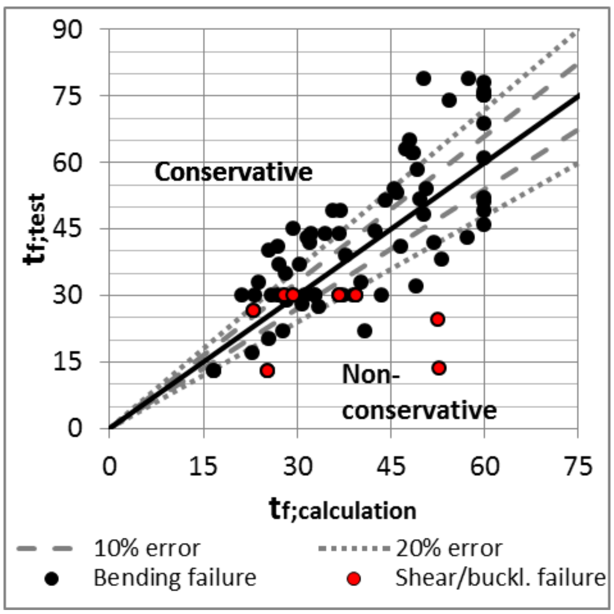

Figure 10: Test results versus predictions of the fire resistance using the **estimated strength; $t_{f;calculation}$ < 60min**

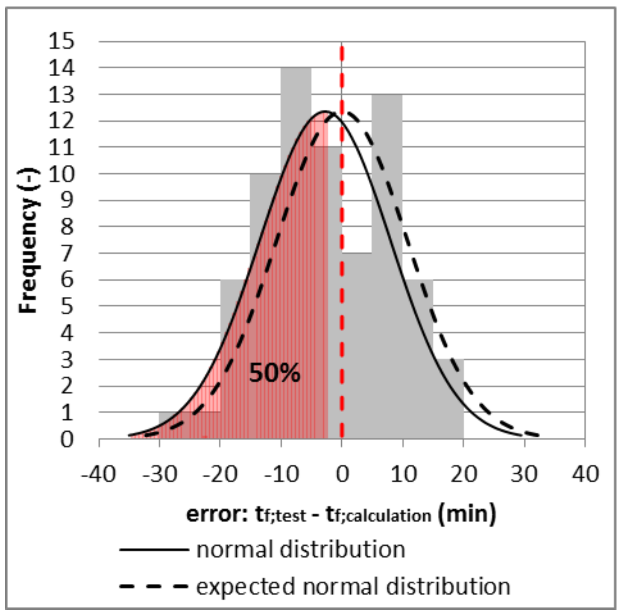

Figure 11: Frequency of errors and the corresponding normal distribution using the RCSM and the **estimated strength; $t_{f;calculation}$ < 60min** (bending failure only)

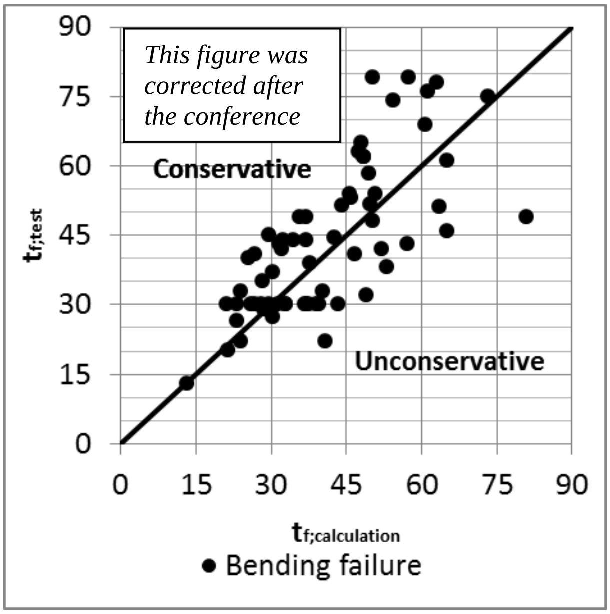

Figure 12: Test results versus predictions of the fire resistance using the **estimated strength; $t_{f;calculation}$ < 150min**

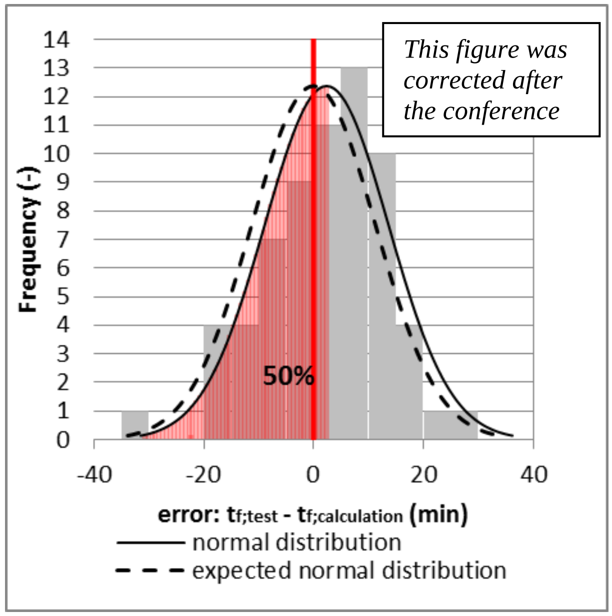

Figure 13: Frequency of errors and the corresponding normal distribution using the RCSM and the **estimated strength; $t_{f;calculation}$ < 150min** (bending failure only)

CONCLUSIONS

In this study the validity of the Reduced Cross Section Method, an available design model of Eurocode 5 (EN 1995-1-2), was investigated. This was done by a comparative study between fire test results of bending tests and predictions using different input parameters for the Reduced Cross-Section Method. The variation of input parameters included (a) the variation of the percentile value of the material strength, i.e. 5^{th} and 20^{th} percentile and (b) the variation of the zero-strength layer, i.e. 7 and 14 mm. It was aimed to compare the statistical distribution of results which are assumed to be normally distributed. By changing the input parameters, it was investigated to which extend the resulting error overlaps a normal distribution where 5% of the results are allowed to be non-conservative.

The following conclusions were drawn from the study:

- The low number of test results limits the validity of a statistical analysis; however, this is a known problem for fire resistance tests where often single results are considered as sufficient.
- Based on the analysis presented here it can be stated that either (i) the material properties, (ii) the Reduced Cross-Section Method or (iii) the grading procedure causes a non-conservative error.
- The study indicates that the use of the percentile strength in accordance with Eurocode 5 for the calculation of the fire resistance of glulam beams is questionable.
- A comparison with a limited certainty suggested that the Reduced Cross-Section Method leads to reasonable predictions if the right strength is used.

- *Note: This conclusion has been adapted after the conference*. Results indicate that more testing is required for the application of Reduced Cross-Section Method for beams with a fire exposure exceeding 60 minutes.

In order to address the above mentioned criticism it is needed to perform systematically organized research on the topic of (A) safety of timber structures in fire in general and (B) the safe use of the Reduced Cross-Section Method. It is proposed to perform a combined testing and advanced simulation approach in order to create a higher number of data for a statistical analysis.

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