ORANGERI – TEST REPORT

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Summary

Six beams of different ages and species were selected and subjected to fire tests, with the goal of determining whether different behaviours of the charring rate would be found. Two tests were used, one large scale, on four of the beams, and a small-scale test on all six beams.

All beams presented charring rates under the value prescribed by the Eurocode 5. No significant difference was found between the beams of different ages. One of the beams which was of a different species burned slower than the others, but only in the full-scale test.

Introduction

The aim of this report is to establish the charring rate of six beams under two different types of fire exposure and determine if significant differences arise.

Four beams of different ages were selected for a full-scale test, in which they were exposed on four sides.

These four beams were subjected to a visual inspection, as well as a 3D scan of their geometry through a LIDAR apparatus (LEICA BK360). A piece of each was preserved for a small-scale test.

They were subjected to a fire test in a small furnace running on the ISO curve for 60 minutes. All four beams were tested together and were hanging vertically into the furnace. After the test, the beams were removed from the furnace and extinguished with water.

The next day the beams were then cut at specific points to measure the charring rate visually. A software was used to measure the remaining cross section of each beam.

Subsequently samples from all six beams were subjected to a small-scale test, in which each sample were exposed to an ISO curve fire for 60 minutes on one side only.

Eurocode 5

For softwood, Eurocode 5 [1] recommends two different charring rates for solid softwood of density higher than 290 kg/m^3, depending on the number of sides exposed to the fire.

If a single side is exposed, the recommended charring rate is 0.65 mm/min. If multiple sides are exposed, it becomes 0.8 mm/min.

Full-scale test

Test procedure

Four of the beams were hung vertically in the furnace, at equal distance from each other. The furnace temperature was determined by means of plate thermocouples evenly distributed around the wooden beams. Before the test the moisture content was measured through the electric resistance method.

The furnace temperature was continuously controlled to follow the standard time temperature curve within the accuracy specified in EN 1363-1:2020 [2].

Beams

Table 1 shows the characteristics of the four studied beams. The rate of growth (RoG) was measured according to EN 1310 [3]. Beams M1, Titan and Stark have higher densities than the M2 beam, which is the only confirmed spruce beam. The M2 beam also has the higher rate of growth. Each beam had one significant crack, with the Stark beam having two cracks on opposite sides.

For logistical reasons, the assembly of the test was performed a week before. Thus, the beams were left unconditioned for a week, bringing each of their moisture content to 16% before the test.

Table 1. Characteristics of the four studied beams.

Beam	Age	Species	Original cross-section [mm]	Density [kg/m³]	RoG [mm/ring]	Cracks
M1	New	Scots Pine	145*145	567	1.64	Single – 45 mm deep
M2	New	Spruce	140*140	427	6.07	Single – 45 mm deep
Titan 1	120 yo	Spruce/Pine	180*180	505	1.95	Single – 65 mm deep
Stark	200 yo	Scots Pine	200*300	603	3.15	Two sides – 65 mm deep

Charring calculations

Square cross-sections

For the three beams with square geometries, the charring rate was measured by measuring the area of the remaining cross-section at the places where cuts were made. The square root of this area gives the length of the side of the equivalent square cross-section. This remaining square is compared with the original square cross-section to obtain the equivalent charring rate *c*, as in the formula:

$$c = \frac{(w - w_c)}{2} \cdot \frac{1}{t}$$

With *w* the original width of the beam parallel to the charring direction, *t* the duration of the fire, and w_c the width of a square with the same area as the remaining cross-section of the beam after fire, with the formula:

$$w_c = \sqrt{Remaining\ Area}$$

The uncertainty on the charring rate is 0.04 for all measurements, estimated from a 5% uncertainty on the measurement of the remaining area, and a three-minute uncertainty on the duration of the fire.

Non-square cross-section

The stark beam has a much more complicated geometry, meaning the approximation of a remaining square cannot be applied.

Instead, the remaining cross-section at the cuts is superimposed to the original cross-section as measured by 3D scanning. The average distance between each original flat side and the corresponding side of the remaining cross-section is then measured to calculate the charring rate, through the formula:

$$c = \frac{\sum_{sides} A_c}{\sum L_{sides}} \cdot \frac{1}{t}$$

where A_c is the measured area of charring on one side of the beam, and L_{sides} the width of that area. An example of this is shown in Figure 1.

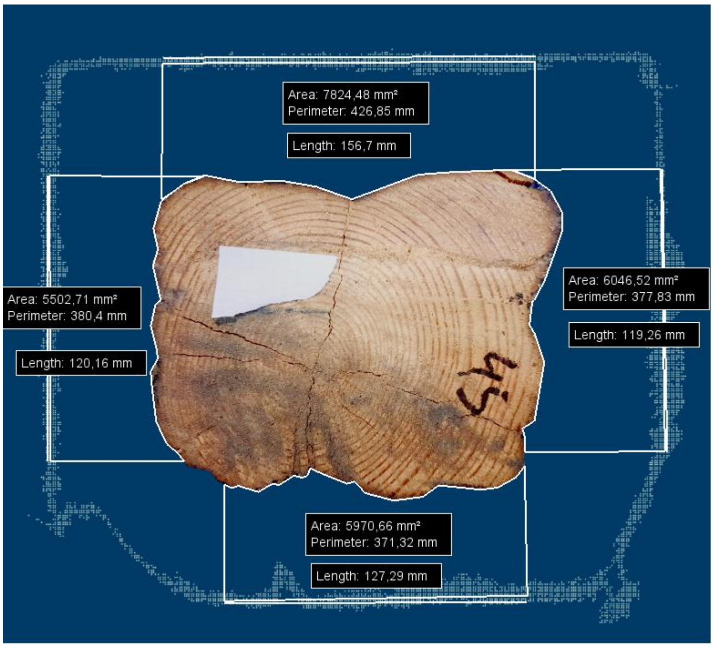

Figure 1. Example of measurements for the calculation of the charring rate of the Stark beam, with a non-square cross-section.

For a square beam, this method would be equivalent to the calculations done previously, and give the same results.

Small-scale test

Test procedure

A sample was cut from each beam. Each sample was 30 mm wide.

The samples were assembled in a single specimen, following the indication of EN 13381. Each sample was isolated from each other and the ends of the specimen by 90 mm of clear softwood.

The specimen was then attached to the ceiling of the furnace and exposed horizontally to a standard fire for approximately 60 minutes.

The order of the samples in the specimen is shown in Figure 1.

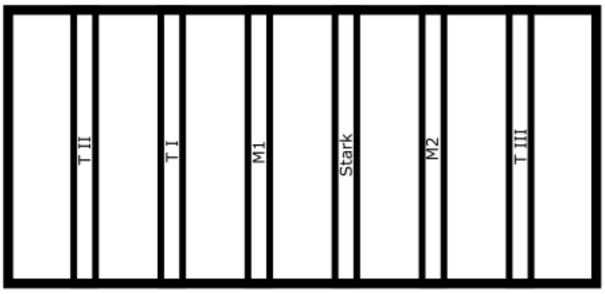

Figure 1. Sample order in tested specimen.

Beams

Table 2 shows the characteristics of the studied beams. Beams M1, Titan and Stark have higher densities than the M2 beam, which is the only confirmed spruce beam. Again, the moisture content was measured right before the test through the electrical resistance.

Table 2. Characteristics of the six studied beams.

Beam	Age	Species	Density [kg/m^3]	Moisture content [%]
M1	New	Scots Pine	567	11
M2	New	Spruce	427	10
Titan 1	120 yo	Spruce/Pine	505	12
Titan 2	50 yo	Spruce/Pine	514	10
Titan 3	70 yo	Spruce/Pine	577	11
Stark	200 yo	Scots Pine	603	13

Charring rate calculations

The charring rate was calculated through two methods.

First, the thermocouples measurements during the test allowed to locate the 300°C isotherm as the test progressed. It can be used to determine the charring rate at that time, through the formula:

$$c = \frac{D}{t}$$

where c is the charring rate, D the depth of a specific thermocouple, and t the time between the start of the test and the moment this thermocouple reached 300°C.

The specimen was also disassembled after the test, and the char layer measured visually.

Results

Full-scale test

Figure 2 shows the charring rate distribution for each cut of the beams. The Stark, Titan and M1 beams have significantly higher charring rates than the M2 beam, with 0.74, 0.76, and 0.68 mm/min for the former, and 0.55 mm/min for the latter. None of the beams showed charring rates higher than the 0.8 mm/min recommended by the Eurocode in this situation.

The beams had comparable moisture content at the time of the fire test (~16%), which cannot explain the difference between beam M2 and the others. It also cannot be explained by the difference in density, as beam M2 has a lower density than the others, which should lead to a higher charring rate. The difference is then attributed to the different wood species.

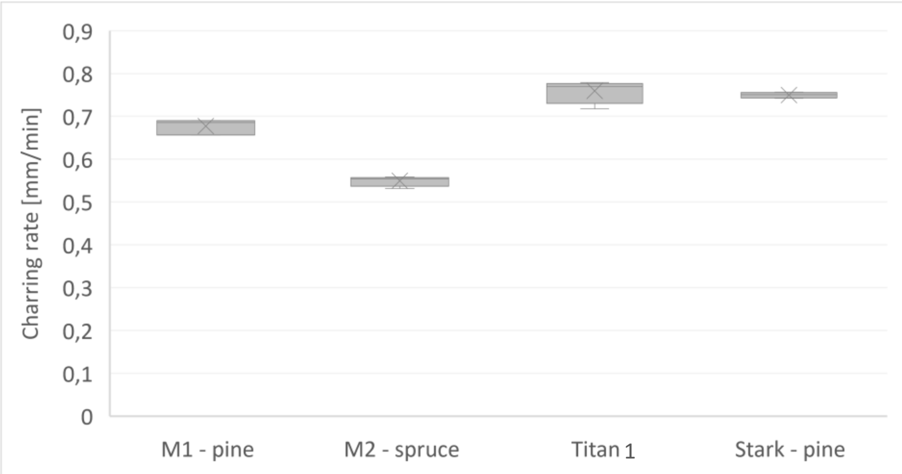

Figure 2. Charring rate distribution for each beam studied.

This conclusion would attribute the species pine to the Titan beam, which had not been formally identified.

Two geometric features were investigated during this test: cracks due to drying, and two 25 mm diameter holes which were drilled through one of the specimens by the previous user.

In both cases, the feature was found to have little to no influence on the global charring rate. There was only a small amount of charring inside the holes, and though the charring was deeper at the location of drying cracks, the effect was not big enough to significantly increase the global charring rate.

Small-scale test

Visual estimation of charring rate

After the specimen was disassembled, the char layer was measured visually. The value found was divided by the duration of the fire to obtain the estimated charring rate.

The results are shown in Table 3. It shows that with the exception of the Stark beam, all charring rates are approximately equal to the Eurocode determined charring rate of 0.65 mm/min.

Table 3. Charring rates of the different samples obtained through visual inspection.

Beam	Charring rate through visual measurement
Titan 1	0.64
Titan 2	0.62
Titan 3	0.65
M1	0.65
M2	0.64
Stark	0.89

Charring rate through the 300°C isotherm

From the temperature measurements of the thermocouples in the samples, the charring rate is estimated at different times during the test. The results for all samples except the Stark sample are shown in Figure 2. The Stark beam showed a higher charring rate, which will be analysed in the next section.

The Titan 2 specimen is not shown in this section, as the measurement of its temperature failed partway through the experiment.

Figure 2 shows that after 30 minutes of fire, the measured charring rates are in good correlation with the Eurocode charring rate.

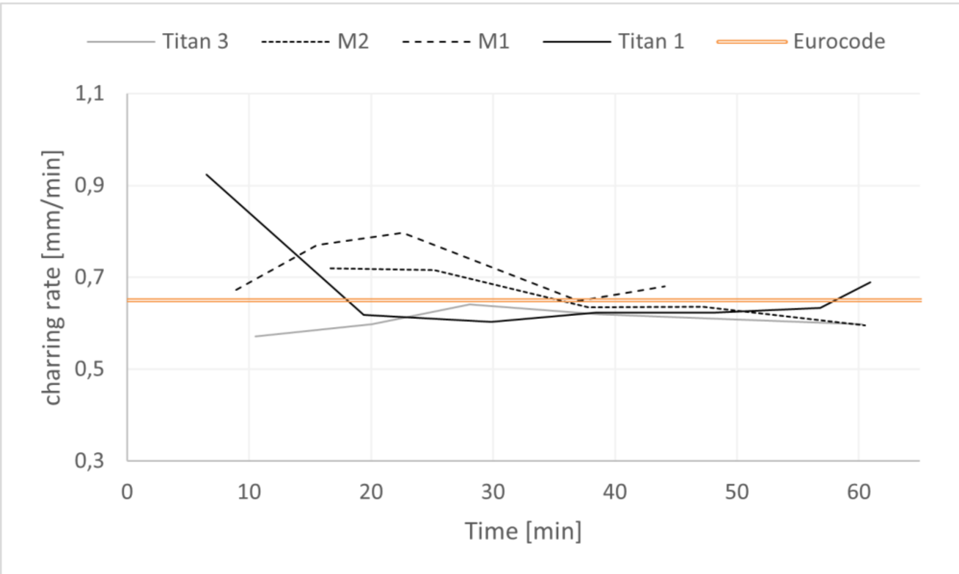

Figure 2. Charring rate during the fire test from the thermocouples measurements, including the 0.65 mm/min Eurocode rate.

The case of the Stark beam

The Stark beam charred significantly more than other beams, both when measured visually and through the thermocouples. Figure 3 shows that the charring rate is always higher than the

Eurocode during the test, going as high as 0.94 mm/min. There is a sudden jump in the charring rate from 15 minutes to 20 minutes.

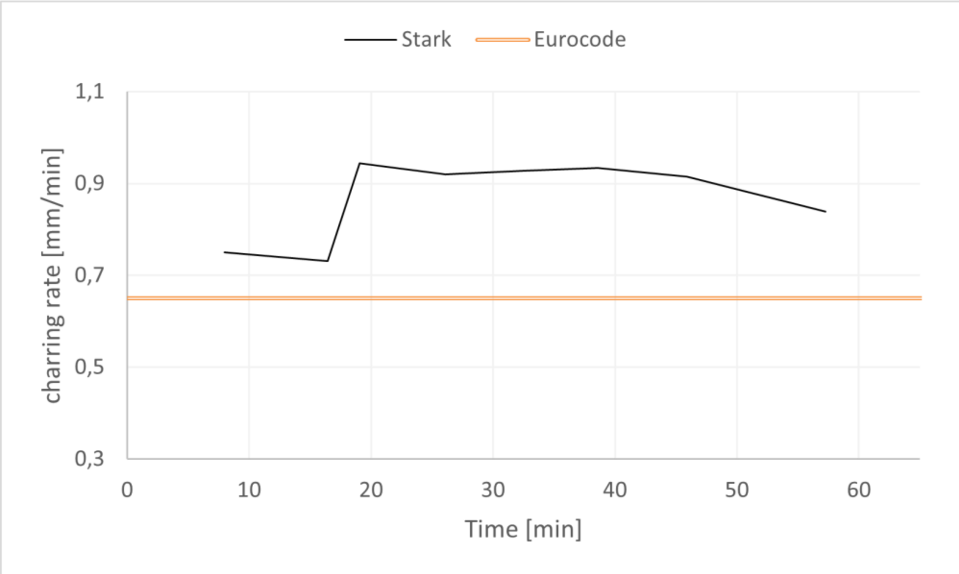

Figure 3. Charring rates of the Stark beam during the fire test, including the 0.65 mm/min Eurocode rate.

Figure 4 shows the char line for the Stark sample as well as for the whole specimen. The char line on the Stark sample is not even, as would have been expected. One side of the sample is significantly more charred than the other, with a rounding effect. On the whole specimen, the Stark sample also appears more charred, as well as the pieces on either side of it.

If the sample simply had a high charring rate, an even char line would be expected. Thus, those results indicate a probable failure of the specimen, causing excess charring on one side of the Stark sample. This failure could come from a delamination between the Stark sample and the buffer, or from an unexpectedly low-quality buffer which burned faster than expected.

Figure 4. Char line of the Stark sample (left) and char line of whole specimen (right), with the Stark sample highlighted.

For comparison, Figure 5 shows the char line inside sample M2, which is almost completely flat.

Comparison of results

For the Stark sample, the results found in the small-scale test indicate a higher charring rate than the one found in the previous, full-scale test. This is another indication of a possible failure of the specimen.

For samples M1 and Titan 1, the charring rate found in the small-scale experiment both through the thermocouples and the visual analysis showed charring rates in accord with the Eurocode, and lower than the ones found in the full-scale test. This is an expected result, as exposure to fire from one side should lead to lower charring than from four sides.

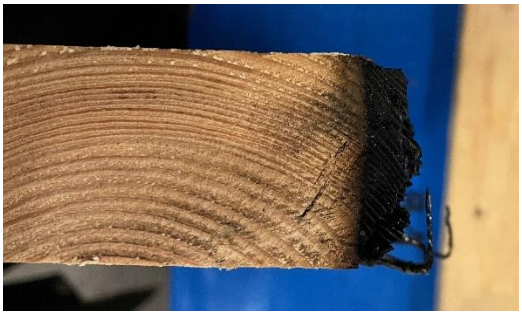

Figure 5. Cut of sample M2, with a very flat char line.

In the full-scale test, sample M2 burned significantly slower than the other three, with an estimated charring rate of 0.55 ± 0.04 mm/min. This was not observed in the small-scale test, where sample M2, the only one made of spruce, burned at approximately the same rate as the others. Its visually estimated charring rate was 0.64 mm/min.

There are two explanations for this difference. The first is errors in measurements, leading to an underestimation in the first test and overestimation in the second. Though unlikely, this option cannot be discarded.

The second explanation brings the method of the small-scale test into question. This test uses pieces of wood as buffer in between the different samples, to insure they may not influence each other. But if those buffers burn faster than the sample does, the assumption of single-sided exposure to fire does not hold anymore. As the buffers burn away, they expose the sides of the sample to the fire.

In this case, a rounding of the char line on the cross section is expected. Observing Figure 5, the char line of sample M2 is almost completely flat.

This means the difference in charring rate cannot clearly be attributed to the test method. It is concluded that the explanation lies in a combination of imprecise measurements and slightly accelerated charring due to the surrounding wood.

Overall, this report indicates that the age of the wood had no effect on its charring rate.

Conclusion

Samples from six beams of different ages and origins were tested in standard fires, with single-side or multiple sides exposure, with the goal of establishing whether differences in burning behaviour arise. The results are shown in Table 4.

Table 4. Result overview of all charring rates

Beam	Single-side exposure charring rate [mm/min] EC5 -> 0.65 mm/min		Four-sides charring rate [mm/min] EC5 -> 0.8 mm/min
	Visual	Thermocouples	
Titan 1	0.64	0.63	0.76
Titan 2	0.62	Failed	Not tested
Titan 3	0.65	0.62	Not tested
M1	0.65	0.66	0.55
M2	0.64	0.62	0.68
Stark	0.89	0.90	0.74

Four of them were tested in a full-scale test in which all four sides were exposed. Their charring rates were determined through visual investigation and the 300°C line in the case of single-side exposure. All six were tested in a small-scale test in which only one side was exposed.

In the full-scale test, three of the four beams had charring rates in good agreement with the Eurocode 5. The remaining beam had an average charring rate of 0.55, significantly lower than the Eurocode prescription. No significant difference was found between the modern beams and the older beams that could not be explained by a difference in density or wood species.

In the small-scale test, five of the six samples had approximately the same charring rate, with no difference between ages up to 120 years old. The charring rates calculated were also well aligned with the Eurocode 5 prescription.

The last sample, from a 200 years-old pine beam, exhibited a charring rate significantly higher than expected. Its char line when cutting into the sample was not flat as expected. This behaviour was attributed to a failure of the test.

Comparing the two tests, two of the beams charred faster in when exposed on four sides, which is the expected result. The two others burned slower in the first test, which is the opposite of the expected result. One of these was the 200 years old beam, which probably experienced a failure during the second test. The other charring rate is explained by a combination of human imprecision during the measurements and issues with the design of the test.

It is overall concluded that the Eurocode 5 prediction of the charring rate was higher than all measurements in either test, aside from the failed measurement of the Stark beam in the small-scale test. No difference was found between the beams of different ages, no influence of the density or moisture content on the charring rate was found. The only notable difference found was that the spruce beam burned slower in the full-scale test than all the other beams.

References

[1] European Committee for Standardization, *EN 1995 (2004) Eurocode 5: Design of timber structures.*

[2] European Committee for Standardization, *EN 1363-1:2020 Fire resistance tests - Part 1: General requirements.*

[3] European Committee for Standardization, *EN 1310 (1997) Round and sawn timber - Method of measurement of features.*

Appendix: Experimental values

Table 1. Charring rate for the modern and Titan beams. The uncertainty is 0.04 mm/min.

Cut number	Equivalent charring rate [mm/min]			
	M1	M2	Titan	Stark
1	0.69	0.53	0.77	0.75
2	0.69	0.56	0.78	0.76
3	0.66	0.55	0.77	0.72
4	-	0.55	0.72	0.73
Average	0.68	0.55	0.76	0.74

Table 2. Char increase due to cracks in the four beams, at each cut. The M1 beam showed no signs of increased charring due to cracks.

Measurement	Char increase due to crack [mm/min]			
	Titan	Stark	M2	M1
1	0.008	0.026	0.008	No visible char increase
2	0.004	0.016	0.007	
3	0.005	0.020	0.003	
4	0.006	0.015	0.009	
5	-	0.017	-	
6	-	0.014	-	
7	-	0.024		
8	-	0.016	-	