EXAMINATION OF THE EFFECT OF FIRE RETARDANT MATERIALS ON TIMBER

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Abstract

The fire safety of structures is an existing and important design aspect, which is assured by strict regulations. As a means to adhere to the strict requirements, fire protection has become a core problem. It is particularly difficult to comply with these regulations in the case of timber, which is a combustible material. These problems could be solved by enveloping the wood in fire retardant materials. MSZ EN 1995-1-2 [1] currently does not take into consideration the fire-retardant materials charring rate under fire exposure. However, currently these fire retardants are prooving to be reliable and depending on their application can achieve better reaction-to-fire classifications. During the research, the authors used 5 different fire-retardant materials on 3 different types of wood and tested their behaviours in a laboratory. When selecting them, it was important to choose the species that are most commonly used in the building industry but which have significantly different densities. Our choice fell upon spruce (360 kg/m^3), scots pine (540 kg/m^3), and oak (650 kg/m^3). During the tests, we examined the weight reduction and the process of burning on the specimens treated with the fire retardant material. In addition, the authors also performed tests by derivatography on both untreated and treated specimens.

The question, is whether the effects of the fire retardants should be taken into consideration when calculating the extent of the burn. The Eurocode [1] does not provide any opinions. On the market, there are manufacturers who are already discussing the possibilities of reducing the burn rate during the qualification of paints. In this paper, based on the results we recieved, we discuss the beneficial effects of the fire retardants which can be taken into account while measuring cross-sections.

Keywords: timber protection, fire retardant materials, fire protection, charring rate

1. INTRODUCTION

1.1 The behaviour of timber in fire exposure

At elevated temperatures, timber undergoes significant chemical and physical transformations. Burning timber experiences a complex chemical process, which contains diffuse combustion, and glow after thermal degradation. During the process of thermal degradation (pyrolysis) combustible gases develop (the stage of gasification), which can inflame near the surface of the timber - this is the flame – which comes with the emission of light. Timber can not only ignite at a specific temperature, but if adequate time is provided, it can even burn at temperatures near 170° C or if there is an activation of energy. This is because the gasses needed for combustion are already released inside the timber before it starts burning, but they do not ignite immediately. In timber, imperceptible chemical processes can occur up to 100-110 ˚C, while still losing its water content. Between 110-150 ˚C due to the acceleration of chemical processes, brown and then black discoloration can be observed. In addition, essential oils are also released in this temperature range. Between 150-200 ˚C, the fragmentation of long cellulose molecules begins to take place. As a result, the generation of gases affect the rate of burning and at the same time the intense charcoal formation begins. This is the process of charring, which occurs between 200-260 ˚C, and at the same time, the quantity of degradation products increase. Carbon monoxide, hydrogen, methane gases are released, which will ignite due to heat, spark, or flame. This state is the flashpoint. Between 260-290 °C, the generation of combustible gases are so intense that the burning becomes continuous. Between 330-370 ˚C the released gases start to burn without the presence of an ignition source, which means the self-ignition point of timber. The process only occurs if sufficient amounts of oxygen is available in the environment [2]. At about 600-700°C, the surface of the wood smoulders, its combustion product, the charcoal, is visible in the fire. The thermal insulating capability of the charred outer layers is overestimated by many engineering studies. The thermal degradation zone (pyrolysis) is located below the fissures and cracks on the surface of the carbon, where the combustible gases get enough space to leave through the cracks and cause further thermal degradation in the wood. The thickness of the charcoal layer is mostly constant, about 1-2 cm. These thicker parts simply fall down and therefore do not work as an insulation
[3-13].

1.2 Fire protection of timber

Since raw timber is essentially a solid fuel, fire-safety regulations prescribe the use of fire protection means for wooden elements, aiming to reach the required levels of resistance-to-fire performance (e.g. load-bearing capacity in fire). Additional fire protection of wooden elements are commonly achieved either by the application of fire retardants (e.g. intumescent coatings, impregnation) or by the installation of fire protection claddings on the fire exposed side of the elements to improve the reaction-to-fire performance [13].

The use of chemical protectants on timber in case of fires has a long history. The first notes of it originates from Herodotus (BC 484-425), from which we can conclude that the Egyptians protected their buildings against fires. Chemical protection was achieved using alum (potassium aluminate sulphate).by M. Pollio Vitruvius, Roman architect (1st century BC) in his book of "The Architecture". From the writings of Aulus Gellius, we know that during the siege of Piraeus (i.e., 87 BC), the towers made of timber were also treated with an alum tincture against fires. Flame retardant coatings have also been made using clay, lime, and alumina. The method of flame retardation hardly changed during the Middle Ages. From the 900s the towns with narrower streets, provided better protection for their citizens against hostile armies, however, they have also increased the risk of fires spreading. [3].

The first scientific experiments on the topic of fire protection are related to a French physicist Gay-Lussac. He experimented with various compounds before 1820 and marked ammonium compounds as the most effective substances. During his tests, he preserved hemp and linen textures. In Russia, Versamm and Oppenheim investigated the flame-retardant effect of substances. They found sodium tungsten, ammonium phosphate and ammonium chloride suitable for this purpose. In 1826 they published the results of their experiments about the generated water glass (sodium silicate), and its application in fire protection.

Since the 1920s, the application of flame-retardant saline solutions have become crucial. Gay-Lussac's statements have been extended by further research over the last hundred years. In general, there are no significant differences in the mixing ratio and the percentages (5-10% solution) of the variants of the ammonium salt, (ammonium phosphate, ammonium hydrogen phosphate, ammonium sulfate, etc.). In the '60s, the development of urea, silicone and dicyandiamide materials started [3].

With the development of military technology and the appearance of phosphorus bombs in the Second World War, the number of fires increased significantly. The significant damage induced

in structures however was not only caused by the combustibility of wood, but also by the limited number of available effective protections. Lots of timber structures were covered by whitewash, which only gives a slight protection. Water-glass preparations (Antifog, Mineralit, etc.) were also used, which are highly effective but have a noticeably short lifetime [3].

Timber and its different substitutes used for wooden structures have differing burning properties. For example, chipboard belongs to the „easily combustible" category, the natural timber, ply timber is "moderately combustible", the particleboards are „hardly combustible" and in some cases, cementitious chipboards are classified as "non-combustible" [4]. The combustibility level of the natural wood also depends on the species of it. The most resistant are acacia, oak, beech. Moderately-resistant materials are larch, pine, black pine. Hardly-resistant materials are spruce, walnut, cherry, and finally non-resistant are fir, alder, linden, and poplar [5].

The fire resistance of wooden elements can be increased by applying a non-combustible, inorganic material, or by using a special chemical-retardant material developed for this purpose. Fire retardant materials form a melted coat on the wooden surface in the presence of heat, which works as a thermal insulator. It slows down the warming process of the interior of the timbers, prevents the release of flammable gases, the coating can also protect the timber from oxygen. Usually, various plastic derivatives or other organic compounds, phosphates, pigments are applied to the timber's surface, where the above-mentioned phenomenon occurs under the influence of heat, reducing the combustibility of the material.

The oldest and most used flame retardants are ammonium-based salt compounds. They are easily degraded by heat, and they prevent the combustion of gases. Particularly, the decomposition of ammonium salts reduces heat, so it cools the surface of the wood. Flame retardant products that contain phosphate salts cause carbonization on the. This thermal insulation layer slows down the heating of the interior. The disadvantages of these types of fire retardants are that they are a highly soluble, thus, the applied salts can be easily washed off. Therefore, they can only be used in environments without direct water access. The desired flame-retardant effect can be reduced or be eliminated in case of a slight condensation.

The fire retardant must be applied on the surface of the wood or it must be saturated by the solution.

Nowadays, many fire retardants - coated, sodden, saturated – can provide a more favourable fire protection classification for combustible materials for a specific period of time. [4] These are the requirements for the fire retardants: highly toxic gases cannot be released during the

combustion, the strength of the wood should not be weakened by it, they should not increase the weight of the structure, surface coatings should be shockproof and durable, they should be applied to or combined with different wood-treated surfaces. They also should dry rather quickly, and the aesthetic appearance of the timber should not be damaged, the protective effect should be durable and also economical.

Flame retardants can work with different mechanisms:

- Mechanical protectants: They make an insulating layer on the surface of the treated wood, this keeps the air (oxygen) as a burning substance away. Mechanical protectants prevent the release of decomposing gases without detaching the insulating layer [3]
- Coat forming protectants: They form a coat on the surface of the desired wooden element under heat. Some of the heat is removed from the environment. In some cases, they facilitate the colouring of the surface of the wood [3].
- Protectants for extinguishing gases: They provide protection, and the protectants (ammonia, carbon dioxide, nitrogen monoxide, etc.) used as aqueous solutions, they also inhibit the penetration of the oxygen into the wood. The heat releases neutral gases, which can inhibit the mixing of gases and air in the degradation process of timber. [3] Another approach is the mechanism of taking action in the gas phase by: when the degradation points of the flame retardant additive is lower than that of the combustible material, and degradation produces a non-combustible gas product, then on one hand as an inert gas, produces a cooling effect, and on the other hand is a dilution gas in case of the lower ignition limit concentration. From this point of view, additives can be water, ammonia, sulphur dioxide and carbon dioxide which are formed as a result of thermal degradation.
- Carbonizing protectants on the wooden surface: highly concentrated inorganic acids. There are no noticeable effects due to the organic acids. Having said that, here is a strong carbonizing effect on some ammonium compounds and their acid formation [3].

1.3 Taking measurements from the wood.

The main method of measuring the wood that was under fire is to cut a cross-section that has already been burned. Then the cross-sectional characteristics (area, inertia torque, inertial radius) are calculated based on the new cross-sectional dimensions.

In order to calculate the part of the wood that cannot be measured as reliably, we need the so-called burn rate and the fire-retardants limit, which is, the time that the structure can stay stable. According to the definition of Eurocode [1], "the burn depth is the distance between the outer surface of the original element and the limit of the burn depth." Furthermore, it should be taken into account that "the position of the limit of burn depth should be recorded at the same temperature as the 300 °C isotherm. So, the burn rate shows how much of the woods thickness burns in a given time. Its symbol is β and the SI units for it is mm/min. The size of the burn rate depends on the species of the tree, i.e. the density of the tree."

In this paper, I will determine, the burn rate of three different densities of trees and examine the effect of density on the burn rate.

Generally, the burn rate is multiplied by the desired fire resistance time

$$d_{\text{char}} = \beta\, t$$

where:

d_{char}	planning value of burn depth;
β	burn rate in case of standard fire effect;
t	duration of the fire effect.

This is clearly illustrated in the following figures:

Eurocode [1] distinguishes two different types of burn depths and burning rates. One is the real burn rate, which can be measured on a burning wood that has a large, flat surface. The other one is a corrected burn rate, which takes into account the increased roundness of the corners due to the burn from more sides.

The question is whether the effects of fire retardants should be taken into consideration when calculating the burn depth. The Eurocode 5 does not provide any opinions on the matter. On the market, there are manufacturers who are already discussing the possibility of reducing the burn rate during the qualification of certain paints.

2. APPLIED MATERIALS AND METHODS

2.1 Applied materials

In our tests, we tried to find a wood species, which is suitable for structural purposes (spruce, popple, oak, acacia, beech, poplar and alder). Our choice fell on spruce, pine, and oak, because their densities and burn rates are significantly different from the rest.

During the tests the three types of wood we used were:

- spruce (360 kg/m^3),
- scots pine (540 kg/m^3)
- oak (650 kg/m^3).

Table 1 shows the main features of the treatment agents we applied. Different types of treatment agents were used in the experimental phase to test their effectiveness against different densities of wood. The treatments differ in their methods of application.

While treating the specimens we followed the instructions of the technical datasheet belonging to the treatment agent, taking into account the applied quantity, the evenness and the time for drying. 4-4 specimens for all timber types and treatments methods were tested, altogether 18×4 specimens were used for our tests, Table 2 shows the experimental matrix.

2.2 Examination of the combustibility of timber

We used the Lindner [5] method during the measurements (*Figure 1*). The steps of the measurements were the followings:

1. Mass of the specimens is measured with an accuracy of 0.05 grams.
2. 1.0 g hexamethylene tetramine paste is prepared, placed on a stand, on a steel cylinder, and then lit up.
3. With the least delay possible, a standard steel funnel is placed on it, and the test specimen is placed on top of the stand.
4. After the flame phenomenon, we wait until the specimen cools down to room temperature and then we measured its mass again.
5. The weight loss is calculated.

Table 1- Main characteristics of the treatment agents.

	Raw material	mechanism of action	experience
paint 1 (water-based)	Water based foamy emulsion coating	It expands (foams) due to fire (or heat) and the thickness of the carbon layer may reach hundred times the original dry thickness.	Treatment with a brush is only enough to handle a smaller surface, but it is also difficult. The paint releases the moistre to the timber as soon as it gets to the surface, therefore it will be dense, so it cannot be applied evenly. Dilution is only possible to a limited extent.
paint 2 (solvent synthetic resin)	Solvent-free synthetic resin dispersion	As a result of direct fire and strong heat, it forms an intumescent layer.	It is only enough for a small surface. The paint releases the moistre to the timber as soon as it gets to the surface, therefore it will be dense, so it cannot be applied evenly. Dilution is only possible to a limited extent. After drying it gives a single, white surface.
marinade	saline	Fire retardant effect is that the treated timber surface is saturated with inorganic salts in the solution. As a result of flame and/or heat effect NH3 released so the timber just burns or charres, but does not burn with flame.	It is a dilute and spreadable watery liquid. It is difficult to absorb into the timber, but a large amount of it needs to be used, that is why, it can be applied in at least 4 layers, because it is flowing. After drying it leaves no traces on the surface, therefore the original pattern of timber remains visible, aesthetically beautiful.
paint 3 (solvent-based)	Solvent based	intumescent timber fire retardant paint	Well spreadable and it will be gelatinous after painting. After drying, it is translucent and shiny.
paint 4 (water-based)	water-based	intumescent timber fire retardant paint	Well spreadable and after painting, it will remain slightly striped and white.

Table 2- Experimental matrix

	spruce	scots pine	oak
paint 1 (water-based)	4 pieces	4 pieces	4 pieces
paint 2 (solvent synthetic resin)	4 pieces	4 pieces	4 pieces
marinade	4 pieces	4 pieces	4 pieces
paint 3 (solvent based)	4 pieces	4 pieces	4 pieces
paint 4 (water-based)	4 pieces	4 pieces	4 pieces
without protection	4 pieces	4 pieces	4 pieces

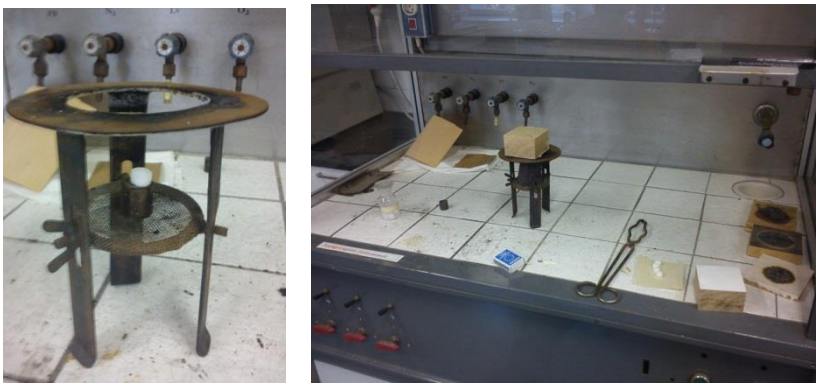

Figure 1- Experimental tools and arrangement for examining the effects of fire retardants

The advantages of the Lindner method [5] is that it is cheaper, simpler, and faster, however, our experiences show that the standard deviation of the results can be higher and does not distinguish between the different types of timber, nor does it take into account the method of application of the flame retardant material. We know that the behaviour of wood is mainly influenced by its type, structure, water content, resin content, anatomical direction of the cut and, last but not least, by its health status. In addition, the weight loss distribution of wood and combustion retardant is not known for total MSZ 9607-1: 1983 within weight loss, although it can be presumed that the former is much greater than the latter. Similar problems were detected in [3] and [6].

2.3 Derivatographic test

For the tests, the specimens had to be cut 1-1 gram of each treated and of a single untreated sample was needed. They were carved from the specimens using a chisel and hammer. In the test samples, the ratio of treatment agent to timber was not important, because we only needed the peaks of mass change for the temperatures we tested, so the samples were taken from the treated surface of the specimens.

The samples were examined in the derivatograph device at a steady temperature for 120 minutes, the applied temperature was between room temperature and 950°C. The used phase analysis method was a so-called derivatographic method. It is a simultaneous thermoanalytical method that simultaneously produces TG (thermogravimetric), DTA (differential thermo analysis) and DTG (derivative thermogravimetric) signals. A small amount of samples are incandesced, placed in a crucible of inert material (corundum or platinum) in a furnace space with a constant heating rate (so-called dynamic mode). Meanwhile, the analytical balance measures the changes in sample mass (TG curve). In addition, the thermocouples measure the heat reactions in the sample in relation to the temperature in the furnace of an inert material (DTA curve). The first derivative of the TG curve, the DTG curve, is produced analogously. This helps to separate the heat reactions associated with mass change. The test result obtained as a function of the measurement time [t (min)] including the three curves and the temperature [T (°C)] is called the derivatogram. It can also be showed as a function of temperature (T °C).

We used the Derivatograph Q-1500 D device for the measurements. The parameters of the derivatographic measurement were as follows:

- Reference material: aluminum oxide
- Rate of heating: 10 °C/min,
- Range of temperature: 20-1000 °C,
- Measured weight of sample: 200 mg,
- TG- sensitiveness: 50 mg,
- Corundum crucible,
- Air atmosphere

We used the WINDER software (Version 4.4) to evaluate the results of the measurements. [7]

3. EXPERIMENTAL RESULTS AND THEIR EVALUATION

3.1 Results of the combustibility test

In *Figure 2* the surface of the treated specimens after incineration is shown, in columns 1-4 the spruce, in columns 5-8 the scots pine and in columns 9-12 oak specimens are placed.

It can b seen that:

- Without any protection, the surface damage was much greater than in case of the protected pieces.
- The damage was always the smallest in the case of oak and the biggest in case of the spruce specimen.
- The treatment with marinade and with paint 3 (solvent-based) was less effective, than the water-based (paint 1 and paint 4) and the solvent synthetic resin-based (paint 2) treatments.

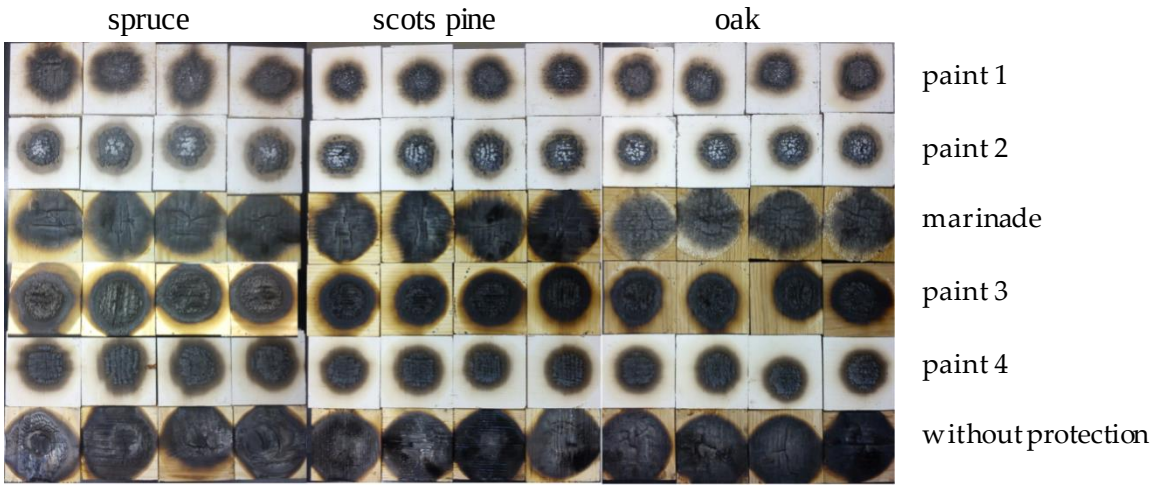

Figure 2 – Surface of treated and untreated specimens after incineration.

From the measurements before and after incineration, the relative weight loss is calculated by comparing the calculated mass loss to the total mass of the specimen. In *Figure 3* we can see the average relative weight loss for different groups of specimens.

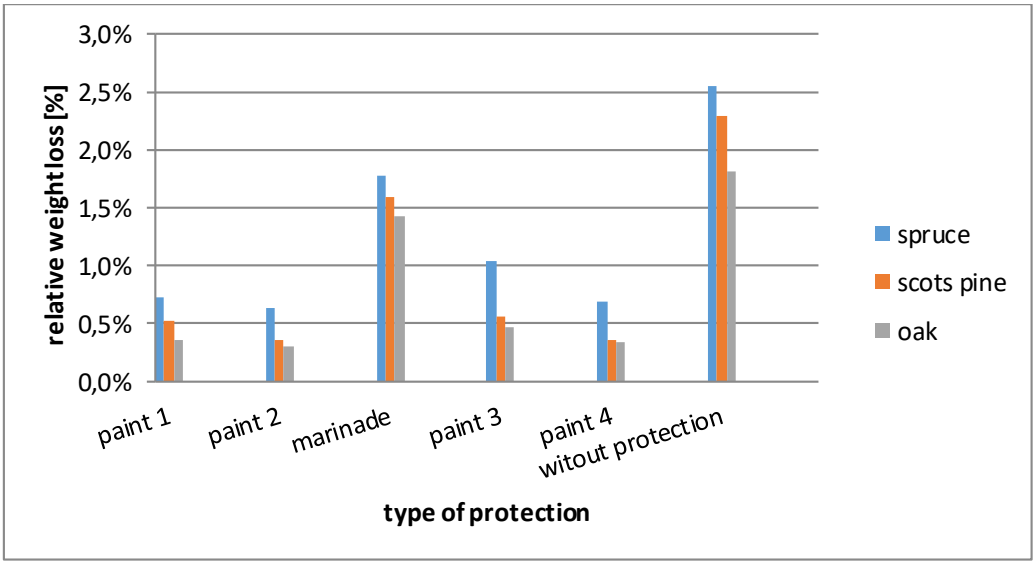

Figure 3 - The average relative weight loss in each groups.

According to the graph, the unprotected specimens and the specimens treated with marinade (salt mixture) suffered the highest relative loss of weight. In case of the paint treated samples, the weight loss was smaller and the relative weight loss was almost the same. It is also clear that the biggest weight loss in each group belonged to the spruce sepcimens, which was followed by the scots pine and the smallest loss occurred in the cases of oak.

It was observed that the weight loss changed with the bulk density of the specimens, therefore the relative weight loss as a function of the density is shown in *Figure 4*.

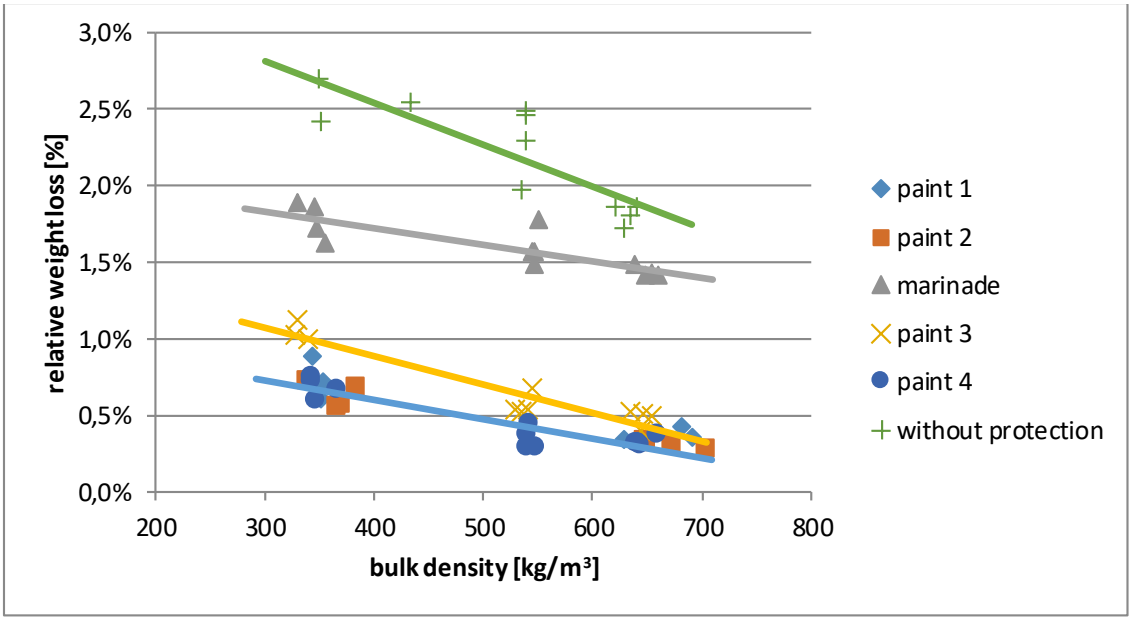

Figure 4 - Relative weight loss as a function of the density

Figure 3 shows that there is approximately a linear relationship between the bulk density and the relative weight loss, therefore, the higher is the density, the less weight is lost. On the chart, the three columns are well separated. These are located around the value of the bulk density of the three different types of tree species. The standard deviation was relatively small. In this case it should be noted that 2 of the 72 test specimens had to be excluded due to their extraordinary behaviour.

The slopes of the trend lines show that in case of low-density wood, the fire retardant paints and salt mixtures (marinades) are more effective than in case of high-density ones. The reason for that is that the protectant penetrates into the pores of the wood easier and deeper and prevents the pyrolysis of gases from flowing into the surface. It also prevents the oxygen from reaching

the surface and consequently the burning. The suitable paints expand, foam is generated, so, they form an insulating layer on the surface of the timber.

The relationship between the fire resistance, the efficiency of the paints and the density of the wood is also shown in this diagram.

Based on our experiments we make the following conclusions:

- **There is a linear relationship between the relative weight loss and the density of wood.** This is true for both unprotected and protected timber. The relative weight loss of unprotected timber is much greater than in the case of the protected one, but the proportionality is visible in all cases. There are several reasons for this. The most important one is that the low-density wood has a more porous structure than the higher density ones. Through these pores, the gases produced during pyrolysis can easily be exposed. In addition, low specific density has a lower specific heat capacity, so it warms up faster and reaches the temperature where the pyrolysis process can occur. Better thermal insulation and lower porosity belongs to higher density, so ignition is hindered.
- **The effectiveness of the protectant is higher in case of low-density timber.** The reason for this is that the protectant penetrates into the pores of timber more easily and to a higher depth. This prevents the pyrolysis of gases and also prevents the oxygen from reaching the surface and consequently the burning.
- **Salt mixture (marinade) means a less effective protection against fire, than the intumescent paints.** This can be concluded because weight losses were higher in case of specimens treated with marinade than in other cases. However, this can be also explained by the different protection mechanism: the foamy paint closes the timber with a thermal insulation layer in case of fire from the source of ignition.
- **Paints can be characterized by the same behaviour as the density of timber:** the results from the experiments of the paint treated specimens are showing a good agreement (*Figure 4*).

3.2 Results of the derivatographic tests

First, we evaluated the results of the unprotected pure oak samples, shown in *Figure 5*, to help comparability with the results of the subsequently treated samples.

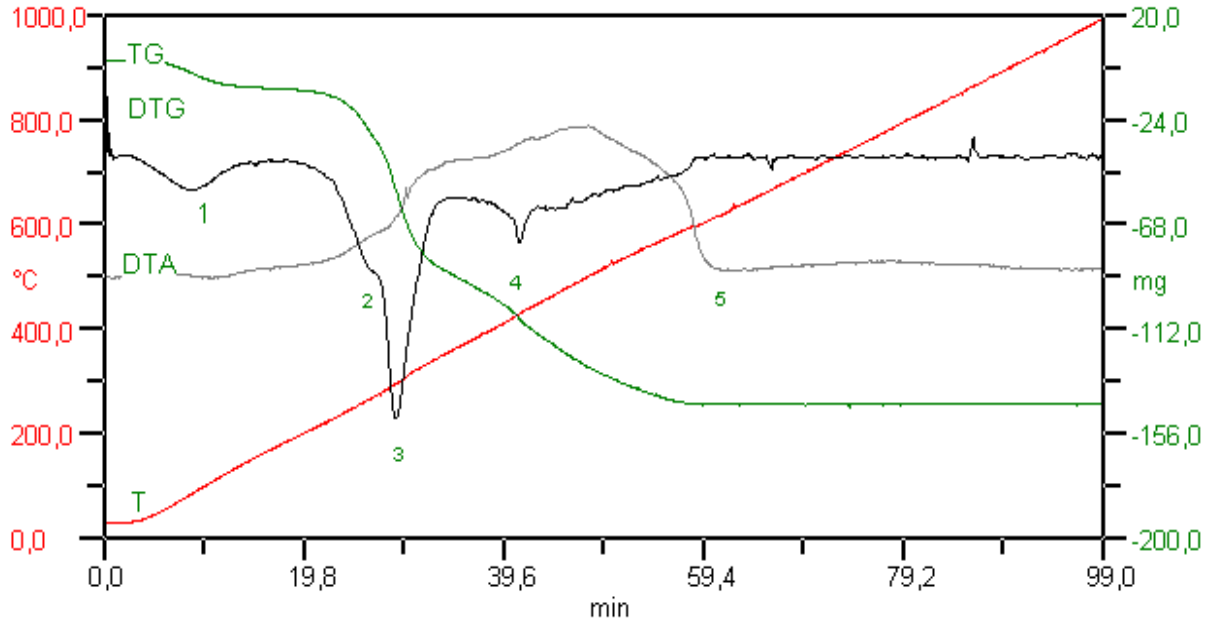

Figure 5– Derivatograph – untreated oak.

It can be seen that the first peak of the DTG curve is around 85 °C. This indicates the release of water from the timber, which was the most intense at this temperature. The temperature of the released water is between 20-152 ° C. The total weight loss was only 8% at this stage.

Between 156-356 °C, essential oils and other gas degradation products were released from the wood, the intensity of this release was the highest at the temperature of 297 °C. The weight loss rate was 54%.

The self-ignition and burning occurred at 359-642 °C. This section of the DTG curve shows that the weight loss rate is relatively even. In this case the weight loss is 39%.

The total weight loss is between 20-980 °C (100%).

Figure 6 shows the thermal degradation peaks. These are the following:

- peak 1: 86 °C
- peak 2: 269 °C
- peak 3: 297 °C
- peak 4: 427 °C
- peak 5: 615°C (end of the weight change)

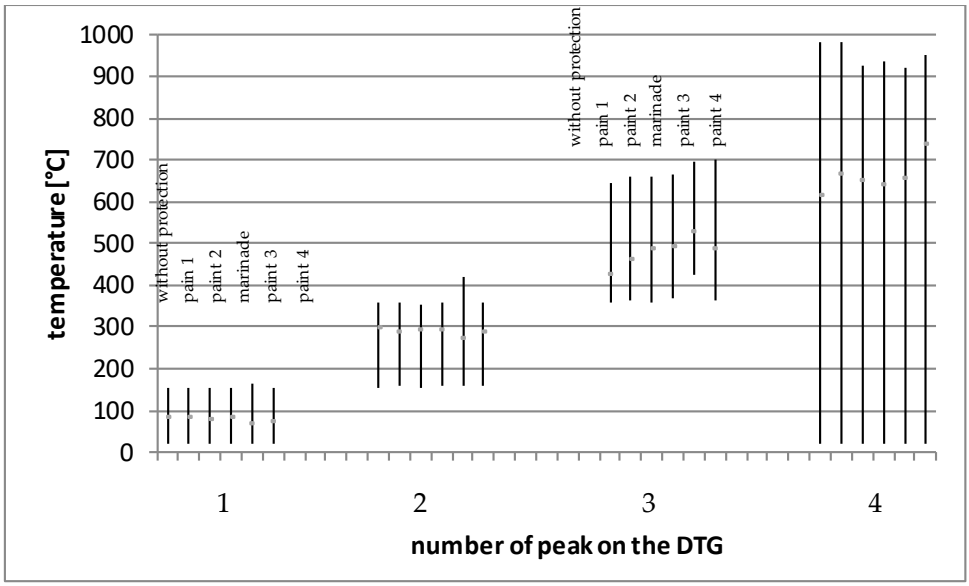

Figure 6 - Comparison of decay steps and peaks.

In *Figure 6* four different groups are separated. The first group shows the lower and the upper-temperature limits for water release (the lower and upper ends of the line), and the maximum intensity (point on the line) for the maximum output. There are no significant differences between the results.

The second group shows the minimum and maximum temperatures for essential oils and degradation gases to release. We marked the temperature of the maximum weight loss rate in the derivatogram by Nr. 3. Each sample is from the left to the right in the same order as in the first group. There is no significant difference between the values here, the ignition was similar in all cases.

In the third group as demonstrated, the upper and the lower temperatures for the burning stages of wood, as well as the maximum burning rate. It can be seen that the temperature at the end of the combustion stage and the highest intensity for the treated samples are higher than in case of the untreated samples. However, in one case even the beginning of the combustion is shifted to a higher temperature. This example shows us clearly the effectiveness of the treatment products.

The fourth group shows the temperature range of the total ignition process and the temperature at the end of the ignition. We can see that the ignition ends at a higher temperature in the case of treated samples than in case of the untreated ones.

4. APPLICABILITY OF THE MEASUREMENT RESULTS IN CALCULATIONS

4.1 Adaptations of the measurements results for calculations

Within each group, we assumed a normal distribution between the results.

Results of all three groups were evaluated by statistical methods:

- We determined the linear function that approximates the values according to the least-squares method.
- We determined the deviation of the individual values from their functions
- We determined the standard deviations
- On the basis of $\Delta\beta=1{,}645*\sigma$ we determined a 5%- quantile
- The line defined in the first point was pushed up with this value

The results are shown on a graph *(Figure 7)*.

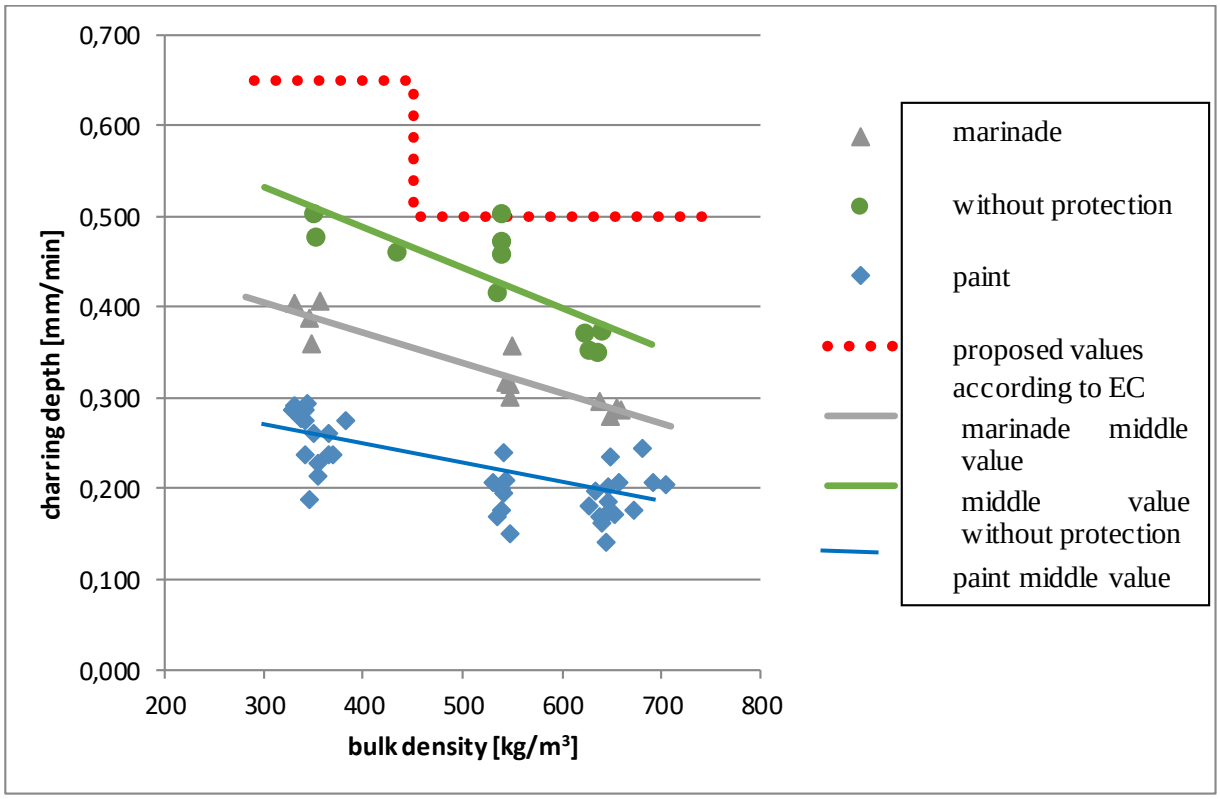

Figure 7 - Burning rates as a function of the density in groups.

For the reason of comparability, the graph also shows the burning rates, recommended by Eurocode [1].

It can be observed from the burning rate of the unprotected specimens that I have experimentally determined the fact that, unprotected trees are well covered by the curve of Eurocode [1], so the results are in fact, authentic. However, the results should be handled cautiously because the combustion was not in accordance with the standard ISO curve and took place within 3 minutes only. Thus, in case of a different sized and a longer fire effect on the specimens, the followings are not necessarily valid. Additional standard experiments are required to verify this statement.

It is also important that these flame retardants can usually exert their effects for about 15 minutes, then they fall off the surface or become ineffective.

Based on the results, a modified burn rate for wood - which is treated with fire retardants - can be proposed as follows:

Table 3- The burning speed

Burning rates	According to EURCODE		Fire resistant marinade		Fire resistant paint	
	β_0 [mm/min]	β_n [mm/min]	β_0 [mm/min]	β_n [mm/min]	β_0 [mm/min]	β_n [mm/min]
a) softwood and beech solid wood, $\rho_k \geq 290$ kg/m^3	0.65	0.80	0.45	0.60	0.35	0.50
b) hardwood solid wood, $\rho_k \geq 450$ kg/m^3	0.50	0.55	0.40	0.45	0.30	0.35

Graphically illustrated in Figure 8.

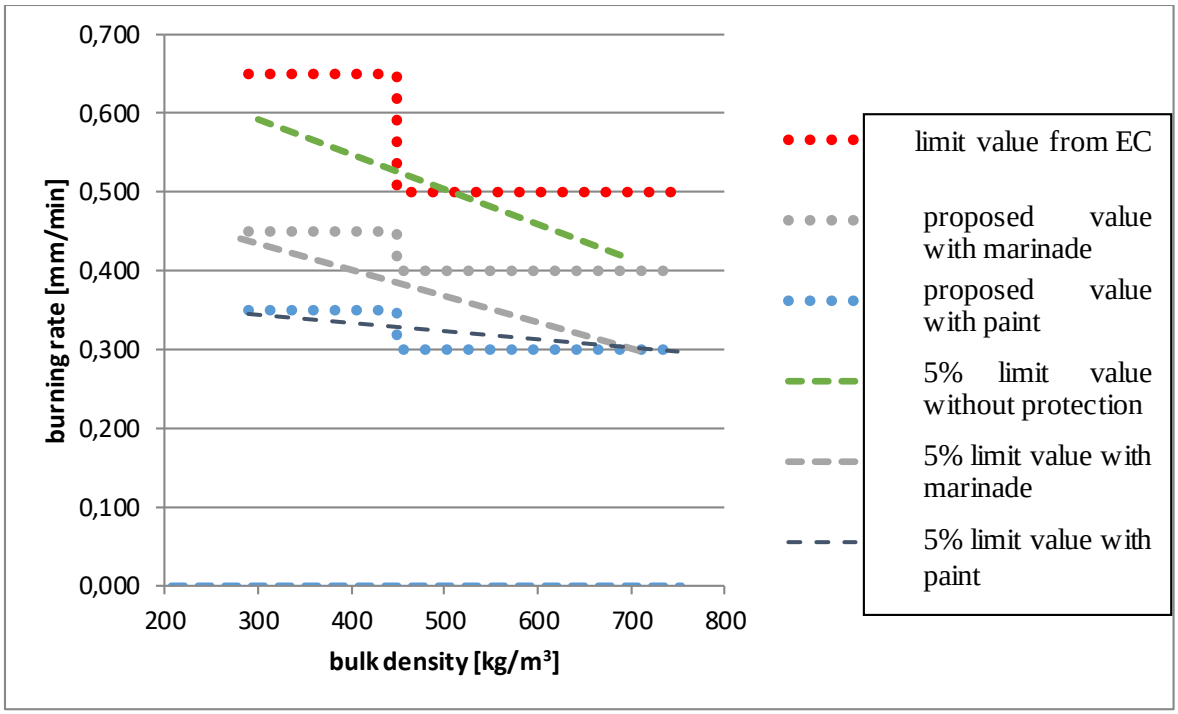

Figure 8- Suggested burning rates.

It means that the burning rate of the fire retardant marinade can be reduced in the case of softwoods by 30%, hardwoods by 20%. Fire retardant paints in the case of softwoods by 50% and hardwoods by 40%.

The above mentioned values refer to a one-dimensional burning rate, i.e. only valid if the following is true:

$$b_{min} = \begin{cases} 2\,d_{char,0} + 80 & \text{ha } d_{char,0} \geq 13 \text{ mm} \\ 8{,}15\,d_{char,0} & \text{ha } d_{char,0} < 13 \text{ mm} \end{cases}$$

If the least page size of the cross section is smaller than b_{min}, then the nominal burn rate must be used. I have proposed a value for the nominal burn rate similar to Eurocode [1].

4.2 Measurement of-a cross-section

To illustrate the extent to which the fire retardant affects the burn depth and thus how much more economical value can be obtained from the cross-sections, we made two comparisons. In the first case, we showed that, in the same initial cross-section, the ratio of the load capacity remains unaffected during a fire retardant period without protection, or in case of using marinade and paint. In the second case, it is shown how much greater cross-sectional area is required in the initial state of the given load, in a fire retardant state therefore, how much economical profits could be made thanks to planning could be thanks to the fire retardants. Based on the above, we considered only 10-, 15- and 30-minute fires.

Columns with square cross-sections between 30 and 150 mm side length were examined for a four-sided fire effect. These sizes are in order of the magnitude of the specimens. For each size, we compared the load capacity after 10, 15, and 30 minutes with the original load capacity, after that this ratio was illustrated against the side length.

We calculated the load capacity ratio as follow:

$$
\begin{aligned}
&\eta_{o.0} := \left|\begin{array}{l}
\text{for } h \in 1..\text{length}(t) \\
\quad t \leftarrow t_h \\
\quad \text{for } j \in 1..\text{length}(a) \\
\quad\quad a \leftarrow a_j \\
\quad\quad k_0 \leftarrow \left|\begin{array}{ll} \dfrac{t}{20} & \text{if } t < 20 \\ 1.0 & \end{array}\right. \\
\quad\quad d_{char} \leftarrow \left|\begin{array}{ll} \beta_0 \cdot t & \text{if } a \geq \min\left(\begin{pmatrix} 2\cdot\beta_0\cdot t + 80 \\ 8.15\beta_0\cdot t \end{pmatrix}\right) \\ \beta_n \cdot t & \text{otherwise} \end{array}\right. \\
\quad\quad d_{ef} \leftarrow d_{char} + k_0 \cdot d_0 \\
\quad\quad \eta_{j,h} \leftarrow \left|\begin{array}{ll} \dfrac{\left(a_j - 2\cdot d_{ef}\right)^2}{\left(a_j\right)^2} & \text{if } a_j - 2\cdot d_{ef} > 0 \\ 0 & \text{otherwise} \end{array}\right. \\
\eta
\end{array}\right.
\end{aligned}
$$

We took into account the acceleration of combustion with the factor $k_{0.}$ The result was: On one hand the burning of the 7 mm pyrolysis zone in Eurocode [1] only takes place after the first 20 minutes. On the other hand, a so-called "discount" is allowed by the side size 1 or 2 dimensional burning, i.e. Eurocode [1]. It means that the cross-sectional side dimension is larger than the size dependent on the burning rate. In this case the rounding of the corners should not be taken into account.

In the above mentioned algorithm, the ratio of the load capacities for time 0 and the fire resistance limit was replaced by the ratio of the area of the original and the burnt cross-sections.

We separately calculated with the values of the β_0 and β_n for the unprotected, the marinade and the paint. After that we illustrated the results on the following graph *(Figure 9)*.

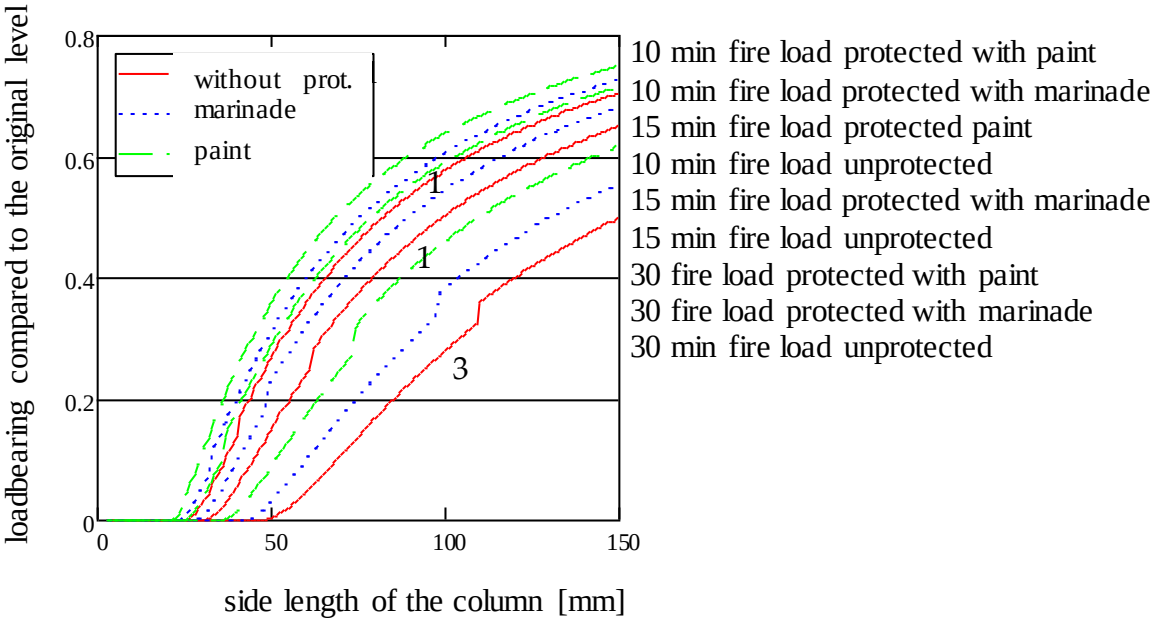

Figure 9- Reduction of the load capacity of the column.

Figure 9 shows the reduction of the load capacity by comparing the loadbearing to the side length of the column. As we can see, in the case of columns with the same side length, the paint-treated load is higher after 15 minutes than the untreated after 10 minutes. In the case of the unprotected fire retardant, a 15-minute limit and a jump of 60 mm can be seen on the graph. This is because at such a rate of burn depth, we can calculate a one-dimensional burn rate above a large size. The same 60 mm jump can be observed on other lines as well.

Compared to the previous method, we calculated the required original size from the required fire size according to the following algorithm:

$$
\begin{aligned}
&a_{o.0} := \left|\begin{array}{l}
\text{for } j \in 1..\text{length}(t) \\
\quad t \leftarrow t_j \\
\quad \text{for } h \in 1..\text{length}(a) \\
\quad\quad a \leftarrow a_h \\
\quad\quad k_0 \leftarrow \left|\begin{array}{ll} \dfrac{t}{20} & \text{if } t < 20 \\ 1.0 & \end{array}\right. \\
\quad\quad a_{o.0_{h,j}} \leftarrow \left|\begin{array}{ll} a + 2\cdot\left(\beta_0\cdot t + k_0\cdot d_0\right) & \text{if } a + 2\cdot\left(\beta_0\cdot t + k_0\cdot d_0\right) \geq \min\left(\begin{pmatrix} 2\cdot\beta_0\cdot t + 80 \\ 8.15\beta_0\cdot t \end{pmatrix}\right) \\ a + 2\cdot\left(\beta_n\cdot t + k_0\cdot d_0\right) & \text{otherwise} \end{array}\right. \\
a_{o.0}
\end{array}\right.
\end{aligned}
$$

By the use of this method, we calculated the required size for marinade and paint. Then we divided the areas of the unprotected calculation with the resulting cross-section areas:

$$\eta_{pác_{i,j}} := \frac{\left(a_{o.0_{i,j}}\right)^2}{\left(a_{o.pác_{i,j}}\right)^2}$$

Based on this, we have shown the results on Figure 10.

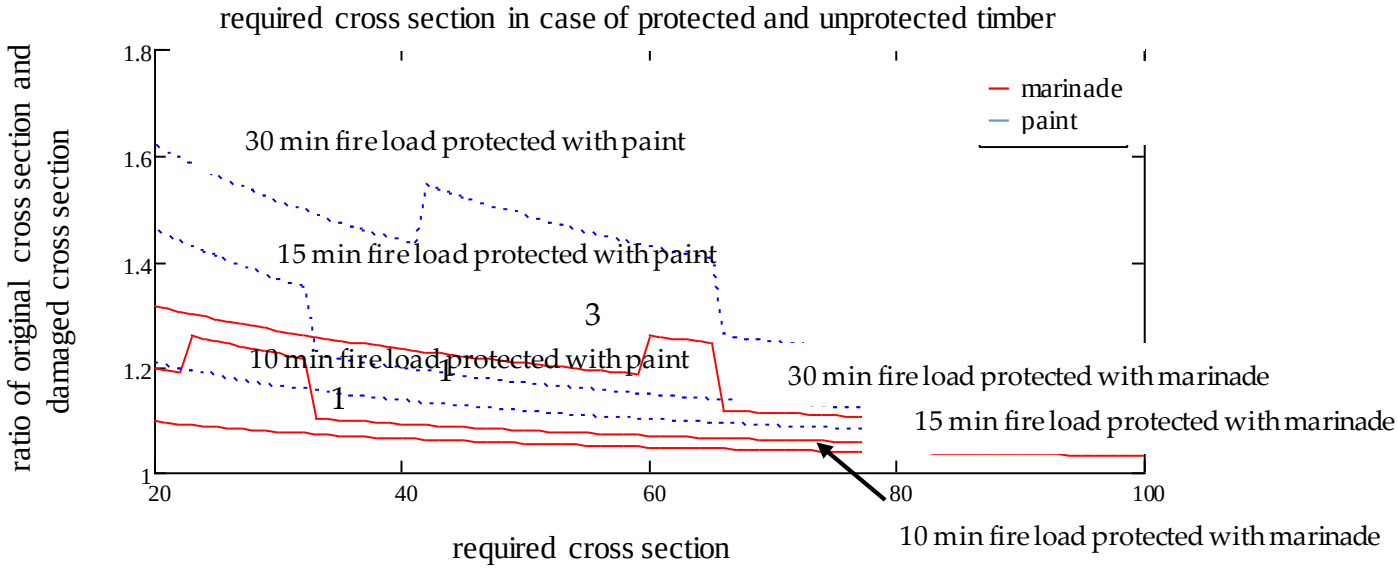

Figure 10- Unprotected and protected columns required cross section

It can be seen that in cases of 10 and 15 minutes we need a cross-sectional area for fire resistance requirements with 10% less, in 30 minutes with 20% less, and for paint with 40%

less. It also appears in self-weight and price. So, whether a fire protection agent is worth the price can be checked also by using this method.

The jumps show in the graphs that there is no limit to the usability of one-dimensional and effective burn depth for treated and unprotected woods.

5. CONCLUSIONS

While conducting our tests, 5 different types of flame retardants were used on 3 types of wood and their behaviors during the fire were observed in a controlled environment. While selecting the appropriate species of wood, our choice fell upon the ones that are normally used in the construction industry, it was also an important factor to choose species that have significantly different densities. In the end our final decision was spruce (360 kg/m^3), scots pine (540 kg/m^3) and oak (650 kg/m^3).

We examined the loss of mass that the specimens treated by different fire retardants endured during combustion. Additionally, we ran derivatographic tests on samples taken from treated and untreated specimens.

Based on the experiments we concluded the following:

- **There is a linear relationship between the relative weight loss and density of the tree.** This is true for both unprotected and protected samples.
- **The effectiveness of the protectant is higher in the case of lower density wood.** The reason for that is the protectant penetrates into the pores of wood easier, deeper and prevents the pyrolysis of gases and oxygen from reaching the surface.
- **Timber treated with a salt mixture (marinade) is less protected against fires, than the intumescent paints.**
- **Paints can be characterized by the same behaviours as the density of timber:** the results from our experiments show that paint treated specimens have good potential.
- **Based on derivatographic examinations**, the temperature range of the burning timber and the maximum burn rate is higher for treated samples, than for untreated samples. It clearly shows us how efficient the treatment products are.

According to the calculations, the following conclusions can be drawn:

- Rapid decrease can be observed when the **load-bearing** capacity of the wooden elements are under 80-100 mm side dimensions. If the size of the cross-section is greater than mentioned above,then it does not cause a significant increase in fire retardant (duration),

only the load capacity increases. Additional time gain can only be experienced when the material was coated by a fire retardant.

- By using fire retardants, a high proportion of cross-sectional area gain can be achieved by using **smaller cross-sections**, therefore it is advisable to use them in situations where there is a little space or instead of a large cross-section that does not have protection.

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