Development of Design Equations for Termoträ Fire Protect for the Component Additive Method

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Introduction

This report details the development of effective thermal properties and design equations for Termoträ Fire Protect which can be used for the improved component additive method for fire design of timber structures.

The initial component additive method is described in Annex E of Eurocode 5 part 1-2 [1] and improved upon by Schleifer [2]. The work of Schleifer greatly expanded the method’s usability and scope by adding main material groups and defining more necessary equations.

With the development of new bio-based and environmentally friendly materials, the question of fire safety prevails. Little is known about such materials and their behaviour in fire scenarios. As the requirements for fire safety are defined in Europe, the need for either testing or calculation possibilities is high. This work describes the procedure used for adding Termoträ Fire Protect to the improved component additive method and provides the design equations.

Termoträ Fire Protect is a cellulose fibre insulation in loose fibre form. It is made from pulp paper by mechanical disintegration. The material has been treated with flame retardant agent and other additives which protect it against other means of degradation (e.g. mould or rodents). It is blown into the structure using special equipment in a dry manner. [3]

The development of effective thermal properties is described based on the work of Mäger [4]. A mathematical iteration method is used and the thermal properties are determined essentially by backwards calculation. As very little test data has been published, these properties shall only be used as effective values as opposed to something inherent to the material.

Based on the effective thermal properties, the design equations are derived according to the procedure described in [2]. These are validated with full scale fire tests where such reports are available.
1 Improved component additive method

The improved component additive method is based on summarising the contributions of each layer to the separating function of a structure considering different heat transfer paths. This method is applicable to timber assemblies consisting of unlimited number of layers of gypsum plasterboards, wood panels, mineral wools and their combinations. A large amount of test data was studied [2] in order to develop the equations.

The total fire resistance of the assembly is the time between the start of the fire exposure and when the temperature on the unexposed side of the structure reaches a temperature rise of 140 K on average over the whole surface or 180 K in a single point. This temperature limitation prevents the ignition of nearby. Generally, the starting (ambient) temperature is 20°C, therefore the temperature criteria become 160°C and 200°C, respectively.

As the assembly can be multi-layered, an agreement on the naming of layers has been made. The symbols used for layer names are shown in Figure 1.

![Diagram of timber frame structure showing layer numbers and functions](image)

Figure 1 – Numbering and function of the layers in a timber frame structure

The insulation time is calculated as shown in (1).

\[ t_{\text{ins}} = \sum_{i=1}^{i=n-1} t_{\text{prot},i} + t_{\text{ins},n} \]  (1)

Where
- \( t_{\text{ins}} \) is the total fire resistance of the assembly [min];
- \( \sum_{i=1}^{i=n-1} t_{\text{prot},i} \) is the sum of protection times of the layers in the direction of the heat flux [min];
- \( t_{\text{ins},n} \) is the insulation time of the last layer of the assembly on the unexposed side [min].

The protection times of layers before the last layer can be calculated taking into account the basic values of the layers, the position coefficients and joint coefficients by equation (2).

\[ t_{\text{prot},i} = (t_{\text{prot},0,i} \cdot k_{\text{pos,exp},i} \cdot k_{\text{pos,unexp},i} + \Delta t_i) \cdot k_{i,j} \]  (2)

Where
- \( t_{\text{prot},i} \) is the protection time of the layer [min];
- \( t_{\text{prot},0,i} \) is the basic protection time of the layer i [min];
- \( k_{\text{pos,exp},i} \) is the position coefficient that takes into account the influence of layers preceding the layer considered;
- \( k_{\text{pos,unexp},i} \) is the position coefficient that takes into account the influence of layers backing the layer considered;
\[ \Delta t_i \] is the correction time for layers protected by Type F gypsum plasterboards or gypsum fibreboards [min];

\[ k_{i,j} \] is the joint coefficient.

Insulation time \( t_{\text{ins},n} \) of the last layer can be calculated taking into account the basic values of the layers, the position coefficients and joint coefficients.

\[
t_{\text{ins},n} = (t_{\text{ins},0,n} \cdot k_{\text{pos,exp},n} + \Delta t_n) \cdot k_{j,n}
\]  \hspace{1cm} (3)

Where

\[ t_{\text{ins},n} \] is the insulation time of the last layer of the assembly on the unexposed side [min];

\[ t_{\text{ins},0,n} \] is the basic insulation time of the last layer \( n \) on the unexposed side [min];

\[ k_{\text{pos,exp},n} \] is the position coefficient that takes into account the influence of layers preceding the layer considered;

\[ \Delta t_n \] is the correction time for layers protected by Type F gypsum plasterboards or gypsum fibreboards [min];

\[ k_{j,n} \] is the joint coefficient.

The coefficients and basic values are dependent on the material of the layer in question and the preceding and backing layers. These values are presented in [5] based on the work of Schleifer [2].

1.1 Insulation materials

Currently only mineral wool insulations are detailed in the method. This situation is clearly not adequate for all the insulation materials currently in the market. Moreover, the materials detailed in the method are all based on tested batt type products.

Generally, the equations for insulation materials include the thickness and density of the material. Density can be a problematic detail for designers as it is not often specified by the producer. Therefore, assumptions must be made which lessen the accuracy of the calculations.

The method assumes a material will have thermally degraded and falls off when the temperature behind it reaches 270°C. Therefore, it should be proven that a new material has the ability to withstand such temperatures. Another important factor is if the insulation is capable of staying in place by itself after the fall-off of previous (possibly cladding) layers.
2 Termoträ Fire Protect

Termoträ Fire Protect is a cellulose fibre insulation mostly produced in the loose fill type. It is made from pulp paper by mechanical disintegration. The material has been treated with flame retardant agent and other additives which protect it against other means of degradation (e.g. mould or rodents). It is blown into the structure using special equipment in a dry manner. [3]

Termoträ Fire Protect is impregnated with 5% Ammonium Polyphosphate flame retardant. A possible mechanism of flame retardance of this additive is its capability of dehydrating cellulose and enhancing char formation. The nitrogen in ammonium can act as a catalyst for the dehydration reaction. [6]

Pure cellulose goes through pyrolysis reactions between temperatures of 315-400°C. After these temperatures a very low amount of weight is left in the form of char. [7]
3 Model scale fire tests

To form the basis for the calibration of thermal properties one non-loaded model scale furnace test was conducted in SP Technical Research Institute of Sweden in Stockholm on the 1st of December 2016.

3.1 Test description

The used test furnace has a volume of 1 m³. It is fitted with 4 burners that use a mixture of propane and butane gasses as fuel. The temperature in the compartment for all tests followed the ISO 834 standard fire curve [6]. The temperature was controlled manually by changing the intensity of the burners.

The test was conducted with a horizontal structure. The specimen was built by Svenska Termoträ and finalised by SP Wood Technology. The specimen was conditioned in a controlled climate chamber (20°C and 65% RH) before the fire tests.

The test specimen was equipped with type K thermocouples placed at different characteristic locations. Throughout the test the temperatures were recorded every 5 seconds. This time step provides good accuracy without making the data so large that it becomes difficult to manage.

The test specimen was built according to the configuration proposed by Schleifer [2]. On the unexposed side was a layer of wood particleboard (thickness 19 mm, density 630 kg/m³). The investigated material – *Termoträ Fire Protect* was blown in with bulk density of 32 kg/m³ with moisture content of 15% by weight.

Test specimen was made without any protective cladding on the fire exposed side. A system with steel net with free expansion possibilities was built by Svenska Termoträ.

See Figure 2 to Figure 14 for drawings and pictures showing the configuration of the test specimen. Red dots indicate the locations of thermocouples.

![Figure 2. Plan of the specimen.](image-url)
Figure 3. Cross section A-A’

Figure 4. Cross section B-B’

Figure 5. Cross section C-C’
3.2 Furnace data

The specimen was tested for 30 minutes in the standard fire. Furnace temperature and pressure during the fire test are presented in Figure 8 and Figure 9.
3.3 Test results

Thermocouple measurements during the tests are presented graphically in Figure 10 and Figure 11.

Figure 8. Furnace temperature.

Figure 9. Furnace pressure.

Figure 10. Thermocouple measurements.
During the fire test the shrinkage of the insulation away from the timber beam was observed (see Figure 13). Some smoke was observed on the unexposed side.

After removing the specimen from the furnace the steel net was observed to not have expanded noticeably. The insulation was in the cavities. See Figure 14 and Figure 15.

**Figure 11. Thermocouple measurements.**

**Figure 12. Specimen during the test. Picture from the unexposed side.**
Figure 13. Shrinkage of the insulation observed from the fire exposed side (21 min).

Figure 14. Removal of the specimen from the furnace.
The timber beam was cleaned from the char and photographed. See Figure 16 for the picture of the whole beam and Figure 17 for the minimum residual cross-section. The charring depth in the middle of cross-section width was observed to be 42 mm.
4 Calibration of thermal properties

4.1 Simulation software

The software used for thermal simulations was SAFIR v2014a1. It is a commercial software developed in the University of Liège [7]. The program can be used to model the behaviour of building structures subjected to fire and to perform a mechanical analysis afterwards. It uses the finite element method (FEM) [8].

SAFIR calculates the field of temperatures that develops during a specified length of time of exposure to a particular fire scenario. Fires can be represented in different manners (time-temperature curves, imposed heat flux or local models) [9]. The structures can be analysed in 2D and also 3D. A two-dimensional specimen with 1D heat transfer path has been used in this case.

The main concept for calculation in SAFIR is that heat is distributed in the structure by conduction since most construction elements are made of solid materials. This means that for some materials the calculation is an approximation. Such materials are, for example, fibrous insulation materials and wood. SAFIR does not take into account the migration of free water and its re-condensation nor heat transfer within the material via radiation between the fibres and air or by air convection. Such limitations mean that the thermal properties used in the conduction model have to be tuned.

On the surfaces heat is exchanged with the environment via convection and radiation. These phenomena are taken into account by specifying the appropriate coefficients. The coefficient of convection on the heated surface is \( \alpha_{c,\text{exp}} = 25 \text{ W/(m}^2\text{K)} \) and on the unheated surface \( \alpha_{c,\text{unexp}} = 4 \text{ W/(m}^2\text{K)} \) as suggested in [10]. The formulas describing heat transfer at the surface and in internal cavities are presented in the technical reference [9].

Calculation within solid materials is based on the Fourier equation (for its representation in Cartesian coordinate system, see (4)).

\[
\frac{\partial}{\partial x} \left( k \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k \frac{\partial T}{\partial z} \right) + Q = c \rho \frac{\partial T}{\partial t} \tag{4}
\]

Where \( \{x, y, z\} \) is the vector of Cartesian coordinates [m]; \( T \) is the temperature [K]; \( k \) is the thermal conductivity [W/(m·K)]; \( Q \) is a term that accounts for internal generation of heat [W/m³]; \( \rho \) is the density [kg/m³]; \( c \) is the specific heat [J/(kg·K)]; \( t \) is time [s].

Formula (4) can be simplified further to express one-dimensional conduction without internal heat generation. This is presented in equation (5).

\[
k \frac{\partial^2 T}{\partial x^2} = c \rho \frac{\partial T}{\partial t} \Rightarrow \frac{\partial T}{\partial t} = \frac{k}{c \rho} \frac{\partial^2 T}{\partial x^2} \tag{5}
\]

From equation (5) it can be seen that thermal conductivity is divided by the product of specific heat and density. This means that theoretically only one of these values needs to be calibrated to fit test data if there is sufficient certainty in the values of the other.
Generally it is simpler to determine the mass loss and therefore the decrease in density. In the following, thermal conductivity and specific heat have been calibrated and density values acquired from separate tests.

4.2 Calibration procedure

This chapter will be focusing on developing the procedure of calibrating the thermal properties for the simulations run with SAFIR software. As stated before, the effective thermal properties are determined by backwards calculation. Little information is available about cellulose insulation materials and their behaviour at high temperatures.

The effective thermal properties are needed to develop the design equations. The calibration was conducted by simulating known configurations (tested configurations) and comparing the simulation and test results.

For the purpose of determining the effective properties, a MATLAB code was used. The working principle is rather simple – it changes some values of the thermal properties in the input file of the simulation software and compares the results with fire test data in the same point. This process is repeated until an acceptable correlation with test results is obtained and the graphs are shifted iteratively closer.

Temperature measurements from Figure 11 were used as the basis for calibration.

4.3 Effective thermal properties for Termoträ Fire Protect

In the following the graphs of effective thermal properties obtained from calibration to fit the unprotected test are presented.

![Figure 18. Effective thermal conductivity curve](image)
These curves yielded the best results in the simulated configurations. It must be stressed that these calibrated thermal properties are generated to provide good results in simulations which unfortunately do not take into account the physical changes in the material. Therefore, even if there is no particular chemical reaction happening in the material at that temperature, there might be cracks forming, which increase the effective thermal conductivity needed as input for the simulations.
5 Design equations

In this chapter design equations are developed for Termotrà Fire Protect. The procedure for developing the design equations is based on the work of Schleifer [2] and it is used for the material in view of this report.

As shown in chapter 1 there are multiple components to be specified for a material to be added to the improved component additive method. For insulation materials, these are basic protection time and position coefficients. All of these values are based on specific simulations conducted with the effective thermal properties obtained in previous chapters. In all configurations different thicknesses were used for the investigated material (40, 95, 120, 145, 160 and 195 mm). This is necessary to provide correlations based on material thickness.

The basic protection time is the time until the temperature rise behind the layer in question is 250 K on average and 270 K in a single point. This work focuses on the average temperature rise up to 270°C (initial temperature of 20°C with the temperature rise of 250°C added).

The simulation configuration for obtaining the basic protection time is presented in Figure 21.

![Figure 21. FE simulations for Basic protection time (INV – investigated material, WFB - wood fibreboard)](image)

The results obtained from simulations with different thicknesses of the investigated material are plotted against material thickness in Figure 22.

![Figure 22. Comparison of FE simulation results and values from proposed formula](image)
The equations for calculating the basic protection times given in [5] are presented depending on the thickness of the material $h_i$.

The basic protection time $t_{prot,0,i}$ according to the FE simulation of the configuration presented in Figure 21 is:

$$ t_{prot,0,i} = 2.3 + 0.14 \cdot h_i \text{ [min]} $$

(6)

For the development of position coefficients, a more elaborate system of FE simulations and configurations was needed.

The position coefficient $k_{pos,exp}$ takes into account the effect the preceding layer (in the direction of heat flow) has on the layer in question. For gypsum plasterboards, the preceding layer could be either a cladding or some type of insulation. This is simplified to some extent in the simulations which are narrowed down to two configurations presented in Figure 23.

The position coefficient $k_{pos,exp,i}$ was developed from the configuration in Figure 23. Initially, the setup was simulated until the temperature between the preceding layer (massive timber panel or stone wool) and the investigated material reached 270°C and the time was recorded as $t_1$. After that, the preceding layer was removed and the simulation continued. When the temperature behind the investigated material reached 270°C the simulation was stopped and the time recorded as $t_2$.

$$ k_{pos,exp,i} = \frac{t_{prot,i}}{t_{prot,0,i}} $$

(7)

Where $t_{prot,i}$ is the protection time of the layer $i$, calculated as $t_2 - t_1$ [min]; $t_{prot,0,i}$ is the basic protection time of layer $i$ [min].

The setup from Figure 23 was simulated with all the different thicknesses of the preceding layer for all the investigated thicknesses of Termoträ Fire Protect (denoted on the drawing as INV). After these simulations, graphs were compiled of the position coefficients versus the protection times of preceding layers which are shown in Figure 24 and Figure 25.
The effect of material thickness on the position coefficient is evident. Based on the equations published in [5], the position coefficients were expressed using the basic protection time and thickness of the investigated layer. The resulting equations for the position coefficient $k_{\text{pos,exp},i}$ are presented in (8) for when the preceding layer is an insulation material and (9) if the investigated material is preceded by cladding.

\[
k_{\text{pos,exp},i} = \begin{cases} 
1 - 0.7 \cdot \frac{\sum t_{\text{prot},p}}{t_{\text{prot},0,i}}, & \text{if } \sum_{p=1}^{i-1} t_{\text{prot},p} < 9 \\
 \left(\frac{h_i}{1420} + 0.42\right) \cdot \left(\frac{t_{\text{prot},0,i}}{\sum t_{\text{prot},p}}\right)^{1.86-0.3\ln h_i}, & \text{if } \sum_{p=1}^{i-1} t_{\text{prot},p} \geq 9
\end{cases}
\]
In the next step, the position coefficient $k_{\text{pos,unexp},i}$ was developed. This coefficient takes into account the effect the backing layer has on the layer under investigation. In [5] the values provided for different materials backed by timber or gypsum are given as 1.0. The work of this thesis confirms this finding as the results of the tests conducted with wood fibreboard or gypsum as a backing layer showed similar results. Based on this, a simulation of the setup presented in Figure 26 is needed.

A layer of 60 mm stone wool insulation is simulated behind a layer of Termoträ Fire Protect. The time required for the temperature to reach 270°C between the materials is recorded as $t_{\text{prot},i}$. Position coefficient $k_{\text{pos,unexp},i}$ is calculated according to (10):

$$k_{\text{pos,unexp},i} = \left\{ \begin{array}{ll}
1 - 0.7 \cdot \frac{\sum t_{\text{prot},p}}{t_{\text{prot},0,i}}, & \text{if } \sum_{p=1}^{i-1} t_{\text{prot},p} \leq \frac{t_{\text{prot},0,i}}{2} \\
\left( \frac{h_i}{660} + 0.3 \right) \cdot \left( \frac{t_{\text{prot},0,i}}{\sum t_{\text{prot},p}} \right)^{0.95 - 0.13 \ln h_i}, & \text{if } \sum_{p=1}^{i-1} t_{\text{prot},p} > \frac{t_{\text{prot},0,i}}{2}
\end{array} \right.$$  

(9)

Figure 26. FE simulation for position coefficient $k_{\text{pos,unexp},i}$ (INV – investigated material, SW – stone wool)

Figure 27. Comparison of FE simulation results and values from proposed formula for position coefficient $k_{\text{pos,unexp},i}$
For a layer of *Termoträ Fire Protect* backed by insulation, the position coefficient \( k_{\text{pos,unexp},1} \) is proposed in (11).

\[
k_{\text{pos,unexp},1} = 0.39 \cdot h_i^{0.136}
\]  

(11)

6 Verification by full scale test (calculation example)

In this chapter the equations developed in chapter 5 are used to calculate the fire resistance of structures and the result compared with the data from a full scale test. For other materials the formulas used are from the European technical guideline Fire Safety in Timber Buildings [5]. If materials used in tests do not have equations in the guideline, calculated results may be substituted with test data.

The test used for verification was of one load-bearing wall element which included light weight studs, boards and blown in *Termoträ Fire Protect*.

The load-bearing elements were wood-based I-beams with the height of 250 mm. The cavities between the beams were completely filled with insulation with the nominal density of 49 kg/m³.

The unexposed (upper) side of the specimen was covered with a 9-mm thick gypsum boards. On the exposed side were 8-mm thick Aquastone boards. The main ingredients are magnesium, sulfate, silicate and EPS granules.

The length of the test was 61 minutes. The separating function criteria were fulfilled after the test, but the termination was requested by the material producers. Load-bearing capacity was exhausted right after the test was stopped.

Layer 1 – Aquastone board (8 mm)

\( t_{\text{prot},1} = 6.78 \text{ min} \) (value from test results, time from the start of the fire exposure until the temperature rise to 270°C was reached)

Layer 2 – *Termoträ Fire Protect* (265 mm)

\[ t_{\text{prot},0,2} = 2.3 + 0.14 \cdot h_2 = 2.3 + 0.14 \cdot 265 = 39.4 \text{ min} \]

\[
k_{\text{pos,exp},2} = 1 - 0.7 \cdot \frac{\sum t_{\text{prot},p}}{t_{\text{prot},0,2}} = 1 - 0.7 \cdot \frac{6.78}{39.4} = 0.879
\]

\[ k_{\text{pos,unexp},2} = 1 \]

\[ \Delta t_2 = 0.22 \cdot t_{\text{prot},1} - 0.1 \cdot t_{\text{prot},0,2} + 3.5 = 0.22 \cdot 6.78 - 0.1 \cdot 39.4 + 3.5 = 1.05 \text{ min} \]

The correction time has been calculated according to FSITB for gypsum plasterboard type F in wall assemblies. It was used here due to the board staying in place for quite long after the temperature criteria was reached.

\[ k_{j,2} = 1 \]
\[ t_{\text{prot},2} = (t_{\text{prot},0,2} \cdot k_{\text{pos,exp},2} \cdot k_{\text{pos,unexp},2} + \Delta t_2) \cdot k_{j,2} = (39,4 \cdot 0,879 \cdot 1 + 1,05) \cdot 1 = 35,7 \text{ min} \]

Layer 3 – Gypsum plasterboard type A (9 mm)

\[ t_{\text{ins},0,3} = 24 \cdot \left( \frac{h_3}{15} \right)^{1,4} = 24 \cdot \left( \frac{9}{15} \right)^{1,4} = 11,7 \text{ min} \]

\[ k_{\text{pos,exp},3} = 0,5 \cdot \sqrt{\frac{t_{\text{ins},0,3}}{\sum_{p=1}^{n-1} t_{\text{prot},p}}} = 0,5 \cdot \sqrt{\frac{11,7}{6,78+35,7}} = 0,263 \]

\[ k_{j,3} = 1 \]

\[ \Delta t_3 = 0 \]

\[ t_{\text{ins},3} = (t_{\text{ins},0,3} \cdot k_{\text{pos,exp},3} + \Delta t_3) = (11,7 \cdot 0,263 + 0) \cdot 1 = 3,1 \text{ min} \]

Total fire resistance of the structure

\[ t_{\text{ins}} = \sum_{i=1}^{i=n-1} t_{\text{prot},i} + t_{\text{ins},n} = 6,78 + 35,7 + 3,1 = 45,6 \text{ min} \]

**Table 1 – Comparison of results of full-scale fire tests and calculated results**

<table>
<thead>
<tr>
<th>Layer no</th>
<th>Material</th>
<th>( t_{\text{ins}} ) [min]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Calculated</td>
</tr>
<tr>
<td>1</td>
<td>Aquaboard</td>
<td>6,78</td>
</tr>
<tr>
<td>2</td>
<td>Termotra</td>
<td>42,5</td>
</tr>
<tr>
<td>3</td>
<td>Gypsum type A</td>
<td>45,6</td>
</tr>
</tbody>
</table>

The calculated fire resistance is conservative compared to full-scale fire test results. This proves that the developed formulas provide safe calculation results.
References


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Our work is concentrated on innovation and the development of value-adding technology. Using Sweden’s most extensive and advanced resources for technical evaluation, measurement technology, research and development, we make an important contribution to the competitiveness and sustainable development of industry. Research is carried out in close conjunction with universities and institutes of technology, to the benefit of a customer base of about 10000 organisations, ranging from start-up companies developing new technologies or new ideas to international groups.