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# PARAMETRIC STUDY OF MODELLING STRUCTURAL TIMBER IN FIRE WITH DIFFERENT SOFTWARE PACKAGES

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***Abstract***. *In a bid to accurately model structural behaviour of timber buildings in fire, a number of obstacles have been identified which must be fully understood before advanced computer modelling can accurately be used to represent physical behaviour. This paper discusses the obstacles, with suggestions on how to mitigate them, incorporating the challenges of using general purpose finite element software. The paper examines modelling with ANSYS, SAFIR and ABAQUS and the individual and collective challenges related to thermal analyses of timber structures in fire conditions. It considers the effects various model parameters (thermal and structural) may have on physical interpretation of experimental data in comparison with the accuracy of numerical solutions. In detail, the study looks at the effects of 1D and 2D heat transfer analyses, finite element mesh sizes, time steps and different thermal property approaches on thermal models of timber members in fires. It further recommends how best to model these structures using the different finite element software packages.*

## 1 INTRODUCTION

The increasing demand for timber as a building material is noticeable all over the world. This is especially true for residential, office and administration buildings as well as special purpose buildings. There are many benefits to using timber structures, such as visual and tactile attractiveness, high energy efficiency, quick erection time and a low carbon footprint. The greatest concerns by authorities over the use of timber as a building material in modern buildings are normally related to fire safety and these concerns are not adequately addressed by design codes.

The fire resistance of timber structures can be assessed by standardised fire tests, such as EN13501-2 [1] or ISO 834 [2], and can be calculated by methods such as those suggested in EN1995-1-2 [3] or NZS3603 [4]. Design standards such as Eurocode 5 part 1.2 [3] allow the use of “advanced calculation methods”, which eliminate the cost of expensive fire testing by using validated numerical finite element (FE) computer models to determine the thermal and structural performance of timber members exposed to fire. However, the use of such software tools requires sufficient knowledge of the material and structural response under fire exposure, sufficient experience of the user to assess the results of the simulation, an understanding of the boundary conditions for heat transfer and structural calculations and, especially, well validated thermal and physical properties of timber materials. Different prior knowledge of users, boundary conditions, and material property selection influence the models that are produced and effectively affect the perceived performance of timber structures in fire. The authors of this paper had difficulties in independently modelling the behaviour of various types of timber structures in fire conditions, and needed to ascertain the effectiveness of their individual software packages for thermal and structural modelling in fire conditions, especially as literature [5] suggests that FE packages do not adequately predict heat transfer in timber structures. The structures the authors tried to model included:

- post-tensioned timber box beams and walls,
- timber and timber concrete composite floor systems and
- metal fasteners and joist hanger connections in timber structures.

As a result, a collaborative research project has been established at the University of Canterbury to compare different finite element software packages used by the authors (ANSYS, ABAQUS and SAFIR) under identical boundary conditions to model timber structures in fire conditions. It is well known that all these software tools solve the same fundamental equations, so it is often assumed they should give the same results with the same input data, but this has never been verified for timber elements. The project is principally of two parts – thermal and structural modelling. This paper reports on the thermal assessment. In particular, it investigates the influence of mesh size, time-step size and two approaches to modelling the influence of moisture on model accuracy. Furthermore this study explores the limitations of the individual software packages and recommends the best ways to accurately achieve comparable results for the different programs.

## 2 SOFTWARE TOOLS USED FOR NUMERICAL SIMULATIONS

For the numerical analyses presented in this paper full versions of the programs SAFIR 2011, ANSYS 12 and ABAQUS 6.10 were used. An overview of each package, its capabilities and limits as well as advantages and disadvantages are discussed.

### 2.1 SAFIR

SAFIR 2011 is a special purpose finite element program developed at the University of Liege, Belgium, for analysing the behaviour of structures under ambient or elevated temperatures. It consists of an integrated thermal and structural analysis program for carrying out 2D and 3D analyses of steel, concrete, timber and composite structures in fire conditions. SAFIR possesses a variety of finite elements such as beam, truss, solid and shell elements for modelling a variety of civil engineering problems. The thermal and mechanical properties of steel, concrete and timber, following the Eurocodes, are incorporated into the program, but one can also use user-defined materials for the thermal or structural analysis [6].

### 2.2 ANSYS

The finite element software ANSYS 12 solves structural, fluid dynamic, acoustic, thermodynamic and electro-magnetic problems and combinations of these. The program allows the user to input all information with a purpose-built design language (APDL) or through a graphic user interface (Workbench), which can read CAD files. For a thermal and structural analysis the user inputs all material properties and heat transfer conditions, both temperature-dependent and directional. The user then specifies user-dependent structural and thermal loads, the kinds of geometry, mesh sizes, element properties, and solution algorithms. Sequential or coupled thermo-structural analyses are possible. The ability to specify each property, boundary condition and load input requires a deep understanding and background knowledge of the software and the system being modelled. The program can be obtained from ANSYS Inc., Canonsburg USA [7]

### 2.3 ABAQUS

The finite element software ABAQUS 6.10 has been developed to solve an array of general purpose finite element tasks, similar to ANSYS, by solving a set of equations implicitly at specified time increments. It also has the ability to solve dynamic problems explicitly using a direct integration procedure, pursuing a desired solution through time without solving a coupled system of equations at each time increment. The program has both the traditional user input file method of building and running simulations and a graphical user interface (CAE) which automates many of these processes and aids in the visualisation of a problem. In terms of heat transfer, ABAQUS 6.10 can perform uncoupled heat transfer analyses, sequentially coupled thermal-stress analyses, fully coupled thermal-stress analyses and adiabatic analyses. The user can specify structural and thermal loading conditions and user-specified regimes, all physical geometry including mesh sizes, element and material properties, boundary conditions and the numerical solution method. The material properties input is both versatile and vast with a huge array of material types available and in CAE there are ready-made functions to account for latent heat and many other thermal parameters. The range of inputs and outputs is vast; care must be taken in understanding how the inputs influence the simulation. The program can be obtained from Dassault Systèmes Simulia Corporation, Providence, RI, USA [8].

## 3 MATERIAL PROPERTIES

Many different proposals can be found in literature for the temperature dependent thermal properties of timber [9-14]. However, to be consistent in the comparisons described here, and in line with current good practice the Eurocode 5 part 1.2 relationships are adopted for conductivity (*k*), specific heat (*c*) and density ($\rho$) (see Table 1). Such relationships account implicitly for the complex physical and chemical phenomena, so that a simple conductive heat transfer analysis can be carried out without requiring many of the physical complexities of timber combustion and charring to be specifically modelled. Thus effects like moisture migration, formation of char, shrinking and cracking of charcoal are represented by adjusted “effective values” rather than using real measured material properties.

Table 1: Material properties used in this study according Eurocode 5 part 1.2

| Temperature [°C] | Conductivity [W/(mK)] | Specific heat [J/(kgK)] | Density ratio [1)] [-] |
|---|---|---|---|
| 20 | 0.12 | 1530 | 1+w |
| 99 | - | 1770 | 1+w |
| 99 | - | 13600 | 1+w |
| 120 | - | 13500 | 1 |
| 120 | - | 2120 | 1 |
| 200 | 0.15 | 2000 | 1 |
| 250 | - | 1620 | 0.93 |
| 300 | - | 710 | 0.76 |
| 350 | 0.07 | 850 | 0.52 |
| 400 | - | 1000 | 0.38 |
| 500 | 0.09 | - | - |
| 600 | - | 1400 | 0.28 |
| 800 | 0.35 | 1650 | 0.26 |
| 1200 | 1.5 | 1650 | 0 |

1) density ratio – ratio of density at specific temperature to dry density

To use more realistic values requires the consideration of more complicated algorithms within the simulation, such as thermal transport by mass flow (moisture movement), the constantly changing geometry, and the formation of cracks in the charcoal introduced by thermal stresses. The complexity of these problems leads to a huge input effort, coupled simulations and long calculation time which the user would normally want to avoid. The basis of the thermal analysis conducted in this work is a heat balance equation obtained from the principles of energy conservation to calculate nodal temperatures and other thermal quantities. This relationship can physically be described for solid anisotropic materials by the Fourier law, stated in equation (1).

$$c_p(\vartheta)\,\rho(\vartheta)\frac{\partial\vartheta}{\partial t}=\frac{\partial}{\partial x}\left(k_x(\vartheta)\frac{\partial\vartheta}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y(\vartheta)\frac{\partial\vartheta}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z(\vartheta)\frac{\partial\vartheta}{\partial z}\right)+\frac{\varepsilon_p}{\rho(\vartheta)\,c_p(\vartheta)} \quad (1)$$

with: $k(\vartheta)$ thermal conductivity [W/mK]
$c_p(\vartheta)$ specific heat [J/(kgK)]
$\rho(\vartheta)$ density [kg/m³]
$\varepsilon$ inner heat generation rate [W/m²]

# 4 PARAMETRIC STUDIES

## 4.1 Setup of 1D and 2D heat transfer examination

The comparative investigations begin with one-dimensional (1D) heat transfer in a solid timber member. To ensure that the different software packages could approximate physical behaviour, a 1D heating test, performed by Konig and Walleij [9] was selected as the basis for the comparisons. The tests, and subsequent numerical modelling, led to the timber properties mentioned in Eurocode 5 part 1.2, which are listed in Table 1. A 45 mm x 95 mm strip of solid timber was exposed to the standard ISO 834 fire curve for 90 minutes. Temperature measurements were taken at various depths into the wood and compared to numerical simulations (Figure 1). In the 1D heat transfer model described here, a 24 mm x 96 mm strip is modelled to be representative of the central strip tested by Konig and Walleij. The moisture content of the timber was taken as 12%, with a bulk density of 480 kg/m³. In the simulations, one narrow side of the specimen was exposed to the ISO 834 fire curve. The applied thermal exposure consisted of a convective and radiative fraction, to effectively mimic realistic heat transfer and heat loss at the boundary surface. The emissivity $\varepsilon$ and convection coefficient $h$ were assumed equal to 0.8 and 25 W/m$^2$K, respectively, as suggested by EN1991-1-2 [15]. For the opposite (unheated) side a convective coefficient of 9 W/m²K (which accounts for both radiative and convective losses) and an initial ambient temperature of 20°C were applied to the surface. The two longer sides were treated as adiabatic surfaces. The temperatures inside the cross-section were measured along the centreline of the specimen at depths of 0, 6, 18, 30, 42, 54 mm away from the fire-exposed surface (see Figure 2). This allowed easier comparison to the Konig and Walleij's [9] fire experiment.

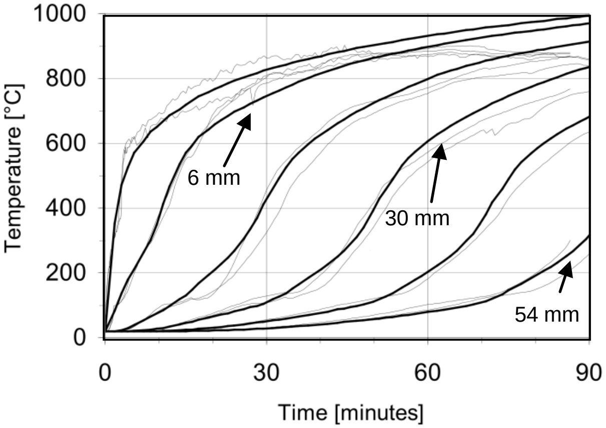


Figure 1. Experimental and numerical results of 1D heat transfer in timber (adapted from [9])

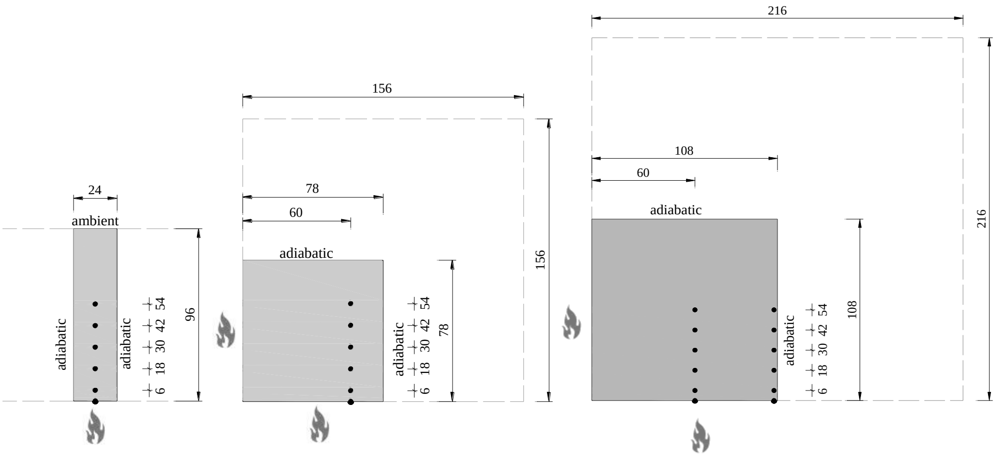
The second step analysed the two-dimensional (2D) heat transfer in a square timber column exposed to the ISO 834 fire on all four sides for 90 minutes. The dimension of the timber column, with an initial moisture content of 12% and a bulk density of 480 kg/m³, was 156 mm x 156 mm. To optimise the setup and runtime, symmetry conditions were used and only a quarter of the section was modelled. Thus the two outer sides were treated as fire exposed and the inner surfaces as adiabatic. For material properties, heat transfer conditions and the locations of temperature measurement inside the cross section, the same values as used in the 1D heat transfer analyses were applied. The column test results and comparisons can be found in [16]. The setup of both assemblies with measurement points and exposure is depicted in Figure 2.The geometries of both assemblies were implemented in the simulation tools and discretised in square meshes with sizes of 1, 3 and 6 mm respectively, using plane elements. The elements had four nodes each with a temperature degree of freedom at each node.

## 4.2 Data input

The influence of temperature on the thermal properties is implemented in the FE software tools used in this study by defining the material through its thermo-physical parameters which govern the heat conduction process. The finite element code allows the user to implement a variation of such quantities with temperature as a piecewise-linear curve. The input of thermal properties into all three finite element software programs was implemented in two separate procedures that considered the inclusion of the initial moisture content differently. The results were then compared to each other.

The more common approach is to use the given material properties in a "*k*-*ρ*-*c* model", with an implicit consideration of a moisture content of 12% in the density function and as heat of vaporisation in the specific heat function. The specific heat capacity is defined as amount of heat which is required to change a unit mass of a substance by one degree of temperature. In SI units this is measured in kJ/kgK. In the case of timber there is a peak in the reported values of specific heat, most commonly taken as between 99°C to 120°C. This is to account for the latent heat of vaporisation of water in the timber, and results in a large increase in energy required to facilitate this phase change.

Alternatively the moisture content can be considered explicitly as a latent heat or enthalpy for a user-specified moisture content. The latent heat model allows for the removal of this peak from the specific heat curve mentioned above, as it specifically accounts for the extra energy of this phase change over the specified temperature range. In ANSYS and ABAQUS these were input into the material models manually, whereas in SAFIR this feature is automatically implemented.



1D 2D (156x156) 2D (216x216)

Figure 2. Setup of 1D and 2D examples (dimensions in mm)

The values for the temperature dependent material properties for conductivity ($k$), specific heat ($c$) and density ($\rho$) were taken from EN1995-1-2 [3], and are presented in Table 1.

### 4.3 Parametric study / Variations

In addition to the two approaches for modelling the effect of moisture content described above, the study also investigated the influence of mesh size and time-step size on thermal analyses of timber structures. Table 2 presents a detailed account of the parameters that were modified in the study. Comparisons of temperatures were performed between the software packages and test results, under each scenario.

Table 2: Overview of variation in the numerical simulations

| | $k$-$\rho$-$c$ model | latent heat / enthalpy model |
|---|---|---|
| FE mesh size | 1, 3 and 6 mm<br>(automatic time stepping - minimum 1x10$^{-3}$ sec, maximum 60 sec) | |
| Time step size | 1, 30, 60 and 120 seconds<br>(with mesh size 1 mm) | |

## 5 RESULTS AND DISCUSSION

For clarity the results mostly show temperatures at 6 mm, 30 mm and 50 mm depths into the heated timber element.

### 5.1 1D heat transfer analysis with "*$k$-$\rho$-$c$ model*"

Figures 3 and 4 show the influence of the mesh size, varying between 1 mm and 6 mm, on the 1D heat transfer problem described in section 4, for the three programs. The results are for the default $k$-$\rho$-$c$ approach. They show that an increase of the mesh size leads to a deviation in the results obtained between the programs. However, there was practically no distinction between the results for the 1 mm and 3 mm mesh sizes, hence the results for the 3 mm mesh are not shown. For the 6 mm mesh size, differences up to 150°C were observed between the different programs. This deviation was most prominent in the temperature range of ~100 to ~500°C and more so at shallow depths, compared with areas deeper in the cross section. It was observed that the results converged after the analyses exceeded this temperature range. Particularly noticeable was that an increase in the FE mesh size (1 mm to 6 mm) produced higher temperatures for ANSYS and lower temperatures for ABAQUS in the ~100 - 150°C temperature range. This shows that the different solver techniques present in each program has an effect on the simulation results. However, all temperatures are an acceptable approximation to the real fire test results.

The analysis of the influence of time-step size showed numerical problems for some programs, because the default numerical convergence criteria could not be met with the $k$-$\rho$-$c$ model. Particularly early in the simulations, with rapid increase in temperature, very small time-steps were necessary to ensure convergence. This resulted in very long calculation times for some scenarios. The analyses showed that if these automatic convergence criteria (of very small time-steps in scenarios with rapidly increasing temperature) are ignored, temperature differences of up to 100°C, for instance, occurred at a depth of 30 mm into the cross-section, with between 1 and 120 s time-step increments.

### 5.2 1D heat transfer analysis with latent heat/enthalpy model

The FE analysis and results showing the influence of the different mesh sizes for the $k$-$\rho$-$c$ model were repeated using the evaporation energy as latent heat. The results were almost identical to those shown in Figures 3 and 4. Further analyses to investigate the effect of time-step size are shown in Figures 5 and 6. It is clear from these figures that choosing time-steps up to 120 seconds has only a minor influence on the results and this can reduce the total calculation time significantly, without compromising the accuracy of the solutions. In comparison to the *k-ρ-c* approach, no numerical instabilities were encountered in any of the programs. Further investigation revealed that time-steps of up to 480 s could be used without any significant loss in accuracy. The negligible differences were most prevalent in the early phase of the fire exposure, where the temperature increase was rapid.

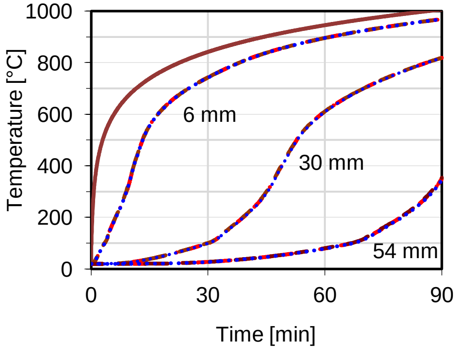


Figure 3. Influence of mesh size and software tool on results for the *k-ρ-c* model with 1 mm mesh size

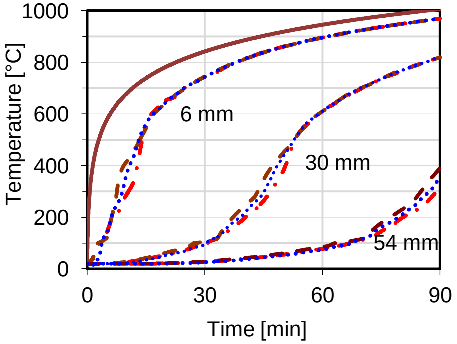
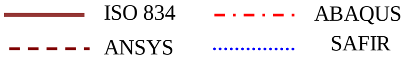


Figure 4. Influence of mesh size and software tool on results for the *k-ρ-c* model with 6 mm mesh size



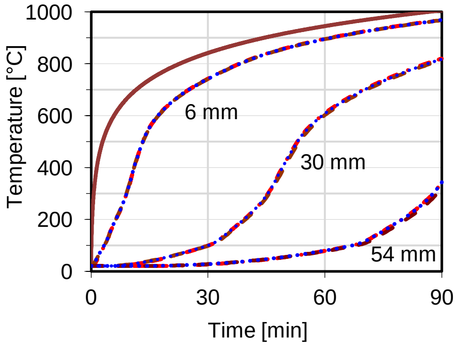


Figure 5. Influence of software tools on results for latent heat model, 1 second time-steps

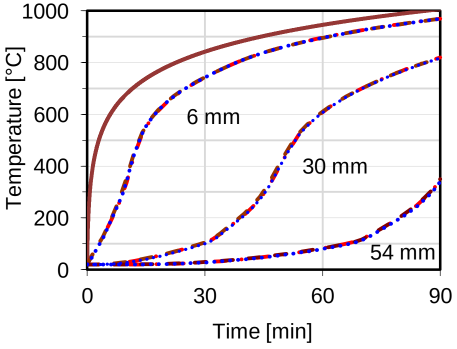


Figure 6. Influence of software tools on results for latent heat model, 120 second time-steps

### 5.3 2D heat transfer analysis

The FE modelling for the 2D heat transfer showed similar behaviour to the 1D heat transfer simulations. Based on the fact that each finite element received considerable heat flow from two surfaces their temperature increase was much faster, and so the deviation in the observed results between increasing mesh sizes (1 mm to 6 mm) became less significant. Thus the smallest differences were found close to the heated corner, where the influence of the 2D heat flow was most significant (see Figure 7), as expected. As described in the 1D heat transfer studies it is observed that the time-step size has a negligible influence when a latent heat model is used instead of the *k-ρ-c* approach for the 2D heat transfer as well. Results of the 2D latent heat/enthalpy thermal analyses in comparison with the test results of the 156 mm x 156 mm column are shown in Figure 7. The numerical results are taken at 6, 12, 18, 30, 42 and 54 mm (as illustrated in Figure 2) while the test temperatures are taken at 6, 10, 20, 30, 42 and 54 mm into the cross-section.

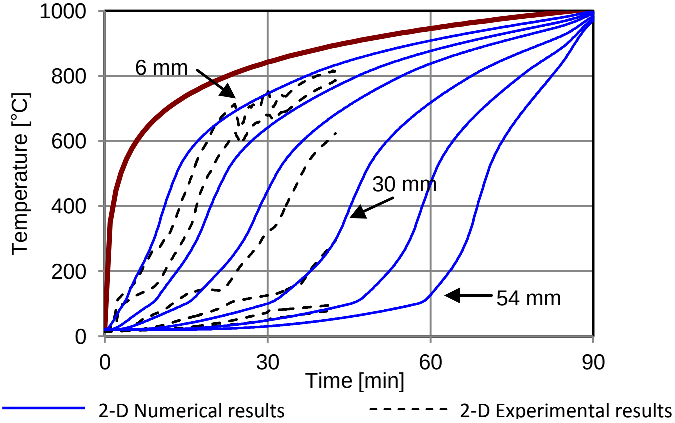


Figure 7. 2D heat flow numerical simulation, compared to experimental results [16]

## 5.4 Deductions

There are occasions where a one-dimensional heating profile is assumed to adequately approximate the heating profile of parts of a timber cross-section, sufficiently remote from a two-dimensional heat source. Examples include the side charring of a timber beam exposed to fire on three sides or wide columns that are rectangular in shape. A brief investigation has pointed to the fact that it may not always be on the safe side to assume a 1D heat transfer. Figure 8 shows temperatures at 6, 30 and 54 mm depths into a column section (216 mm x 216 mm) exposed to fire on all sides, as depicted in Figure 2. It further shows temperatures at the same depths, but at distances of 60 and 108 mm from the heated corner, and results of a one-dimensional heat transfer analysis superimposed on the 2D results. It is observed that the 1D approximation gets worse the further the position of interest is from the heat source and the surface of the cross-section. Hence, for accurate structural simulation of cases of this nature, a 2D thermal analysis should be employed.

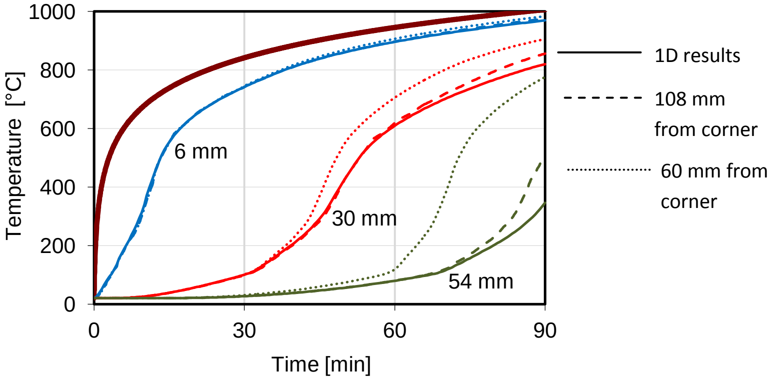


Figure 8. 2D heat flow numerical results compared to 1D results

For structural analysis of timber under fire conditions temperatures over 300°C are normally neglected, because of the minor load bearing capacity of charcoal. Thus temperature readings above 300°C can be neglected for the comparison in this study as well. On that basis, it is observed that the choice of software can influence the calculation of charring rate, depending on the desired fire resistance time. Figure 9 (which is based on a 1D heat flow numerical simulation with 6 mm mesh size and $k$-$\rho$-$c$ approach) shows that ANSYS reports a char depth of 21 mm at 30 minutes of fire exposure while ABAQUS quotes 24 mm. At 60 minutes the char depths differ by about 1 mm. This discrepancy disappears with small mesh sizes and increase of heat flow – a further incentive to use smaller mesh sizes for accuracy.

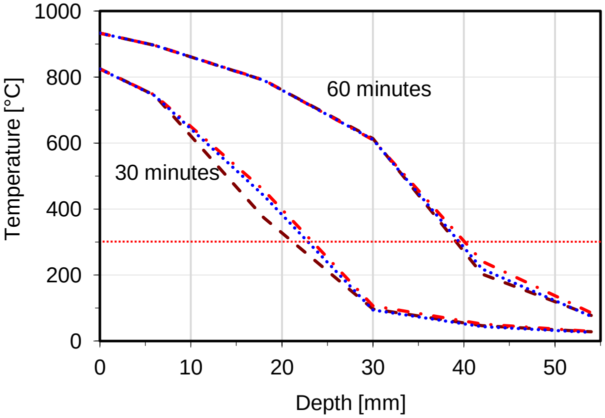


Figure 9. Temperature-depth profile for 6mm mesh, compared to a 300°C isotherm

## 7 CONCLUSION

The results show that the approach used to account for the moisture content of timber in numerical simulations has a large influence on the temperature development. To avoid numerical problems and long calculation times, a latent heat or enthalpy model is recommended. To optimise calculation time, at the beginning of the simulation when there is a rapid temperature increase in the ISO 834 fire curve, smaller time-steps up to 120 seconds should be used. Further on, larger time-steps and the use of an automatic time-step is recommended.

Due to the negligible differences between 1 and 3 mm mesh sizes, as compared to 6 mm, it is recommended that an initial mesh size of 3 mm is used for simple heat transfer analyses in timber, to ensure accuracy while saving on computational time.

Further recommendations:

- checking of the mesh size suitability into the analysis (as the study shows that for elements with a higher rate of heat increase the mesh size can be increased with negligible effect on the results).
- Particular attention should be paid to areas of impinging 2D heat flows, to ensure the mesh size used is appropriate for the desired application.

The research shows that by being cautious of the advantages and limitations of each of the three software packages and approaches, accurate approximations of the thermal behaviour of timber structures can made. It also concludes that the programs give comparable results to each other and real fire tests.

The project further seeks to investigate the influence of different temperature-time curves and explore the development of appropriate models for monitoring structural performance of timber buildings in fire conditions.

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