Calculation Model for Predicting Fire Resistance Time of Timber Members

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ABSTRACT

In the frame of a research program a basis for the realistic simulation of timber structural members in case of fire was developed. Using the finite difference method, a computer program was developed to analyse the behaviour of timber members under fire exposure. The fire resistance time of wooden columns as well as wooden beams with and without axial compression can be determined. In this case the charring rate is not fixed but in a preceding thermal analysis it is calculated as a function of parameters such as moisture content, temperature level, exposure time, cross-section area etc.. The temperature influence on the thermal and strength properties as well as the geometrical and physical non-linearities were considered.

KEYWORDS: fire resistance time, timber members, calculation method, natural and standard fire, combined thermal and mechanical exposure

INTRODUCTION

Wood is a hygroscopic and highly polymeric organic material. Its properties are influenced by factors such as density, moisture content, species, knots, growth rings and the alignment of the grain [1]. The study of fire resistance properties of wood has a special value because of its usage for building material as well as for furniture.

When wood begins to burn, a layer of charcoal develops, which insulates the uncharred wood from the heat of the fire. So, the increase of the temperature of the inner part of the wood is retarded significantly. That is the reason why timber constructions maintain a substantial part of their load bearing capacity during exposure to fire.

Traditional methods for calculating fire resistance time of timber members are simplified methods [2] based on standard fire tests. The shortcomings of such methods (e.g. limitation to standard fire, non economic results for special cases, insufficient accuracy) have intensified the need for more flexible analytical methods.

The aim of the research project was to develop an analytical approach to analyse fire behaviour of timber members under standard fire as well as under natural fire conditions. In the course of investigation influences of moisture content, temperature level, exposure time, size and area of cross-section, mechanical loading on fire resistance time of spruce were studied [6].

THERMAL ANALYSIS

To calculate fire resistance of timber members, the charring rate and the distribution of temperature within the cross-section are required. Investigations in the concerned area have shown that the combustion of wood can generally described by four processes:

- heating up and drying out of the surface zone,
- pyrolytic decomposition of wood in solid and volatile parts,
- combustion of the volatile parts,
- combustion of the solid parts.

With pyrolytic temperature an irreversible process of decomposition by thermal degradation starts. The rate of decomposition depends on temperature level and exposure time mainly followed by other factors such as furnace conditions, cross-section area and existence of catalysts.

The volatile products such as Carbon Monoxide, Hydrocarbon Compounds, Water Vapour, Tar and Benzole participate in the combustion by mixing with oxygen at the surface. Four different zones appear parallel to the heated surface:

- charlayer with a temperature above 300 °C,
- wood in thermal decomposition,
- wood before pyrolytic ignition (about 250 °C) down to the initial temperature,
- and wood with initial temperature and moisture.

Fundamental equations for the thermal analysis are equation (1) for conservation of energy and equation (5) for mass balance in conjunction with pyrolysis respectively. Equation (1) considers thermal conduction, radiation and convection from heat source, heat of vaporisation and reaction energy of pyrolysis products corresponding change of density according to equation (5). The solution of the partial differential equations (1) and (5) yields the temperature distribution T(x,y,z,t) as well as density distribution. Considering the areas corresponding with density of charcoal charring rate can be determined.

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}(\lambda_x \frac{\partial T}{\partial x}) + \frac{\partial}{\partial y}(\lambda_y \frac{\partial T}{\partial y}) + \frac{\partial}{\partial z}(\lambda_z \frac{\partial T}{\partial z}) + Q_1 + Q_2 + Q_3 \qquad (1)$$

where Q_1 = energy transfer (radiation and convection) from heat source
Q_2 = reaction energy in conjunction with pyrolysis of wood
Q_3 = energy in conjunction with vaporisation of initial moisture content

$$Q_1 = \alpha_{tot} \cdot \frac{\partial T}{\partial x} \tag{2}$$

$$Q_2 = \dot{m} \cdot q_{reaction} \tag{3}$$

$$Q_3 = \dot{m} \cdot H_w \cdot \frac{u}{100} \tag{4}$$

where α_{tot} = total value of coefficient of heat transfer (radiation and convection), W m^{-2} K^{-1}
$\dot{m}$ = rate of decomposition, kg m^{-3} s^{-1}
$q_{reaction}$ = heat of reaction, J kg^{-1}
H_w = vaporisation heat of water, J kg^{-1}
u = initial moisture content, %

Decomposition of wood in conjunction with equation of Arrehnius is determined according to equation (5). Some material properties used for thermal analysis are given below (e.g. Fig. 1).

$$\frac{\partial \rho}{\partial t} = -K(\rho - \rho_c) \tag{5}$$

$$K = K_0 \cdot e^{-\frac{\Delta E}{RT}} \tag{6}$$

where ρ = local density of pyrolysing material at time t
ρ_c = density of charcoal, 95 kg/m^3
K_0 = reaction rate constant, 4.10^8 s^{-1} [9]
ΔE = activation energy, 95-124.10^3 J mol^{-1} [9]
R = universal gas constant
T = absolute temperature

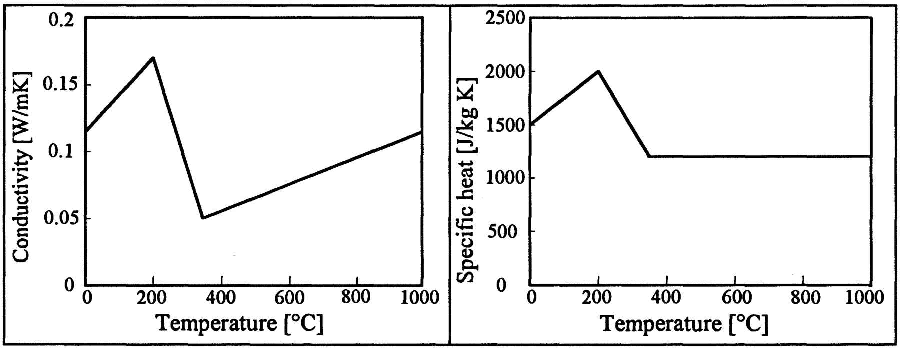

FIGURE 1. Conductivity and specific heat of wood (spruce) dependent on temperature

Along member axis thermal condition can usually be assumed as constant. The equation (1) for heat transfer can be simplified for two dimensional case. By applying the finite difference method the cross-section has to be divided into a lattice of elements. To achieve a high accuracy the size of elements was limited to $\Delta x = \Delta y = 2{,}5$ mm. For the time increment a value of $\Delta t = 3$ seconds was used. Through exploitation of the symmetrical conditions dependent on sides exposed to fire the amount of the elements can be reduced up to a quarter.

By systematic computer supported parameter studies the significant influence of temperature level, exposure time, moisture content, number of sides exposed to fire and shape of cross-section area on charring rate and temperature distribution within cross-section could be quantified [6]. As an example Fig. 2 shows temperature distributions in a cross-section exposed to fire.

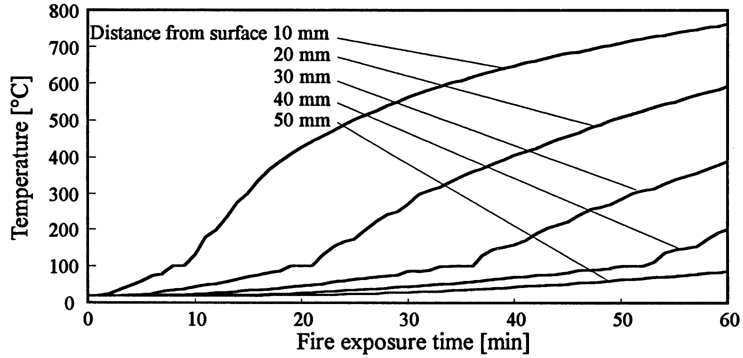

FIGURE 2. Temperature distribution within a cross-section of 140 mm X 140 mm (spruce, u = 12%) exposed to ISO standard fire

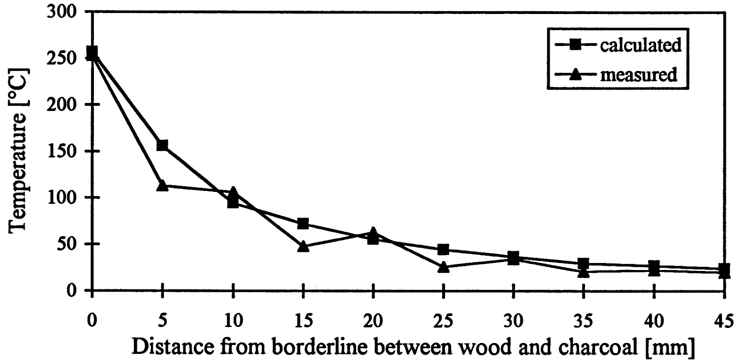

FIGURE 3. Temperature profile within a residual cross-section of spruce exposed to standard fire, comparison between calculation and measurement

The validity of the model for thermal analysis has been verified by simulation of experiments carried out at University of Munich. Fig. 3 demonstrates a comparison between calculation and measurement [7] for a sample of spruce with 12 % moisture content under standard fire conditions.

MECHANICAL ANALYSIS

For a realistic simulation of the load bearing capacity of timber elements at normal condition as well as at elevated temperature, an accurate understanding about strength properties of wood is required. Experiences have clearly indicated that in a given compression area of cross-section stress is no more directly proportional to strain. The form of stress-strain curve in the compression area depends on factors such as density, moisture content, compression wood ratio, wood species [1]. In case of fire it depends further on temperature level and exposure time [3, 8, 10, 11].

The curve of stress-strain for tensile area indicates a linear elastic behaviour at normal condition as well as at elevated temperature up to the point of the failure [3].

Mechanical behaviour of wood at elevated temperature

The temperature dependency of strength properties of wood has been investigated by several authors [3, 8, 10, 11]. Temperature level, exposure time, change of moisture content, etc. have significant influences on strength properties. Investigations have shown that strength decrease is more significant for compression than for tension.

The non-elastic behaviour of compression area for mechanical analysis is described by equation (7). The flexible shape of equation (7) makes it possible to approximate stress-strain curves under normal condition as well as under elevated temperatures. Changing the values n, $f_{c,u}$ and $\varepsilon_{c,u}$ any shape of stress-strain curves can be simulated as shown in Fig. 4. The values n, $f_{c,u}$ and $\varepsilon_{c,u}$ can be determined experimental for different temperatures. For computer simulation results of experimental studies are used [3, 11]. Fig. 5 demonstrate the principle of stress-strain curves for different temperatures. The values n, $f_{c,u}$ and $\varepsilon_{c,u}$ has been used for spruce with 12 % moisture content are listed in table 1.

$$\sigma = f_{c,u} \cdot \left[1 - \left(1 - \frac{\varepsilon}{\varepsilon_{c,u}} \right)^{n} \right] \tag{7}$$

where σ = stress in compression area
$f_{c,u}$ = compressive strength
$\varepsilon_{c,u}$ = the considered strain at the $f_{c,u}$

The distribution of the modulus of elasticity for compressive area, which depends on stress and temperature distribution, has been determined by means of the secant modulus method (Fig. 7).

TABLE 1. The values used for the generation of stress-strain curves in compression area

Temperature [°C]	n	$\varepsilon_{c,u}$ [‰]	$f_{c,u}$ [N/mm^2]
20	1,3	- 3,8	32,0
50	1,4	- 3,8	27,5
100	1,6	- 3,9	22,0
150	1,8	- 4,0	18,0
200	1,9	- 4,1	11,0

Assumptions for calculation of ultimate load

The mechanical analysis of timber members has been carried out using the same discretisation as for the thermal analysis. For calculation the following assumptions are made:

- The influence of temperature level on mechanical behaviour is considered. Each element in discretised cross-section indicates a separate stress-strain curve according to Fig. 5. By means of interpolation the decisive values for different temperatures can be calculated.
- Considering constant thermal conditions along the member axis the mechanical analysis is reduced to two dimensional state. In this case the calculation is required for the weak point of the member. That can be for example the point with maximum deformation because of mechanical exposure.
- Cross-section is symmetrical with the load acting steady in the plane of symmetry only. Lateral buckling as well as local removal are excluded.
- Influence of the shear force on the moment-curvature relation is not taken into account.
- Bernoulli hypothesis applies even if plastic deformations occur in the cross-section.
- Second order theory effects are considered. Because of decrease of cross-section area and stiffness the deflection as well as bending moment M are not constant during the fire. By using initial curvature geometrical and structural imperfections are included.

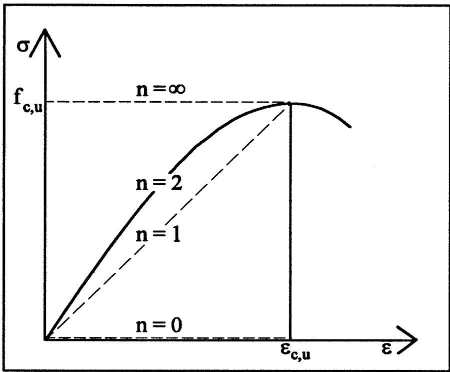

FIGURE 4. Generalised stress-strain curve in the compression area

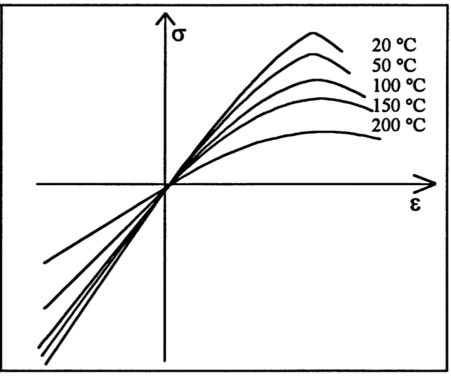

FIGURE 5. Stress-strain curves at different temperatures

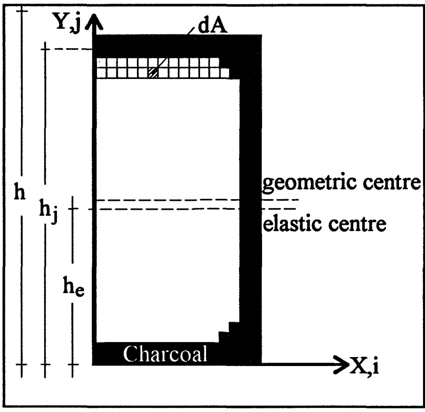

FIGURE 6. Discretised cross-section

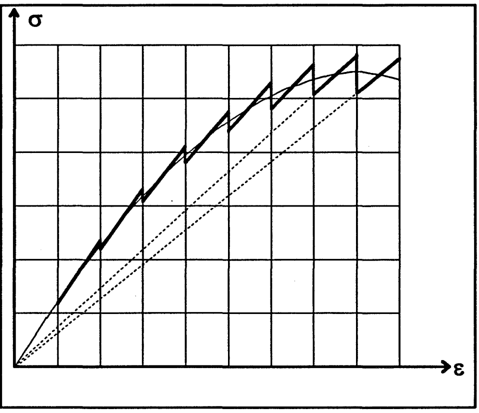

FIGURE 7. Generation of modulus of elasticity in compression area

Calculation of failure time

The load bearing capacity of timber members in case of fire decreases because of reduction of cross-section area as well as stiffness. Failure time is defined as time when the load bearing capacity is reduced to acting external loads (see equation (14)). In this case the deformation grow infinitely without load increase and causes failure of the timber member. The process of calculation of failure time includes following step by step procedure:

1. By thermal analysis combining equations (1) and (5) temperature and density distribution at each time (t) are determined.
2. In all elements where density corresponds with charcoal modulus of elasticity $E_{i,j(T)}$ will be taken as zero. In the remaining cross-section initial values of $E_{i,j(T)}$ are calculated analogous to tensile area. Influence of temperature on stress-strain curves are considered (Fig. 5). The geometrical centre of gravity is supposed as neutral axis for the first iteration.
3. The strain distribution is calculated corresponding to initial $E_{i,j(T)}$ values and external forces M and N (see equations (8), (9) and (10)). In dependence on strain distribution the values for $E_{i,j(T)}$ and the position of neutral axis are corrected.

$$\kappa = \frac{M}{EI} \tag{8}$$

$$\kappa = \frac{|\varepsilon_C| + |\varepsilon_T|}{h} \tag{9}$$

$$\varepsilon_N = \frac{N}{EA} \tag{10}$$

$$h_e = \frac{\sum\limits^{i,j} E_{i,j(T)} \cdot h_j \cdot dA}{\sum\limits^{i,j} E_{i,j(T)} \cdot dA} \tag{11}$$

$$N_{internal} = \int_{A(t)} \sigma(t, \varepsilon, T)\ .dA \qquad (12)$$

$$M_{internal} = \int_{A(t)} \sigma(t, \varepsilon, T) \cdot d_j\ .dA \qquad (13)$$

$$t_u = (t\,(R(t) \leq S) \qquad (14)$$

where κ = curvature
EI = bending stiffness
ε_c = strain at compression edge due to bending moment
ε_T = strain at tensile edge due to bending moment
ε_N = strain due to normal force
EA = strain stiffness
$A_{(t)}$ = cross-section area at the time (t)
$d_{i,j}$ = distance of element to the neutral axis
h, h_j, dA = see Fig. 6
R(t) = internal resistance of member
S = member stress (external loading)

4. By means of equilibrium between internal and external forces and adjustment of stiffness the final strain distribution and the pertinent neutral axis will be calculated as an iterative process (see Fig. 9). Internal forces are obtained as the integral of the stresses of the cross-sectional area according to equations (12) and (13).

   Through iteration two cases are possible:

- For given external loads equilibrium can be found. By Calculating the failure load dependent on ultimate deformation in a second procedure the current safety factor γ can be determined.
- Deformations and stiffness are diverging for the given load. Failure time can be calculated (see Fig. 9).

APPLICATION AND VERIFICATION

The mechanical analysis of timber members in case of fire has shown, that apart from temperature level and exposure time effects such as area and size of cross-section, stress level, slenderness and number and location of exposed sides have a significant influence on fire resistance time.

Based on the above described analytical model a computer program has been developed. All subroutines are written in FORTRAN 77. Verification was done by recalculation of a lot of different fire tests on structural members [6]. For column tests table 2 illustrates the accuracy of the program. The computer program has been used to support accompanying studies required for the final draft of the structural fire design part of Eurocode 5 [5].

TABLE 2. Failure times of wooden columns under standard fire, comparison of model predictions and test data

Specimen	N	Cross-Section		Length	Failure Time [min]	
-	[kN]	h [mm]	b [mm]	l [m]	Tests [4]	Calculated
1	834,5	28	560	5,91	63	57
2	379,3	28	56	5,91	96	91
3	379,3	28	56	5,91	96	91
4	415,8	28	28	5,93	50	46
5	1695,4	28	112	5,82	66	63
6	95,1	14	14	3,22	17	18
7	190,2	14	28	3,22	22	22
8	86,4	14	28	3,22	34	37
9	86,4	14	28	3,22	35	37
10	285,3	14	42	3,22	22	23
11	380,4	14	56	3,22	22	23

The computer program can be also applied to optimise the design of timber members. As examples for optimisation some results are given in Fig. 8: for statically design of wooden beams only slender cross-sections are favourable. However slender cross-sections have a larger surface and are not optimal for thermal exposure. The computer program can be used in this case to optimise the design of timber structural elements (Fig. 8).

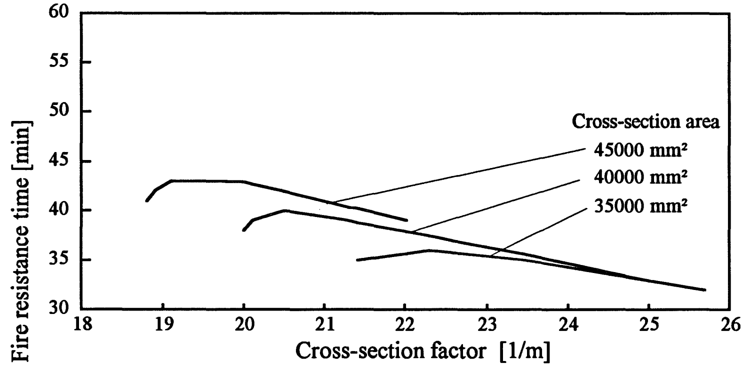

FIGURE 8. Optimisation of fire resistance time

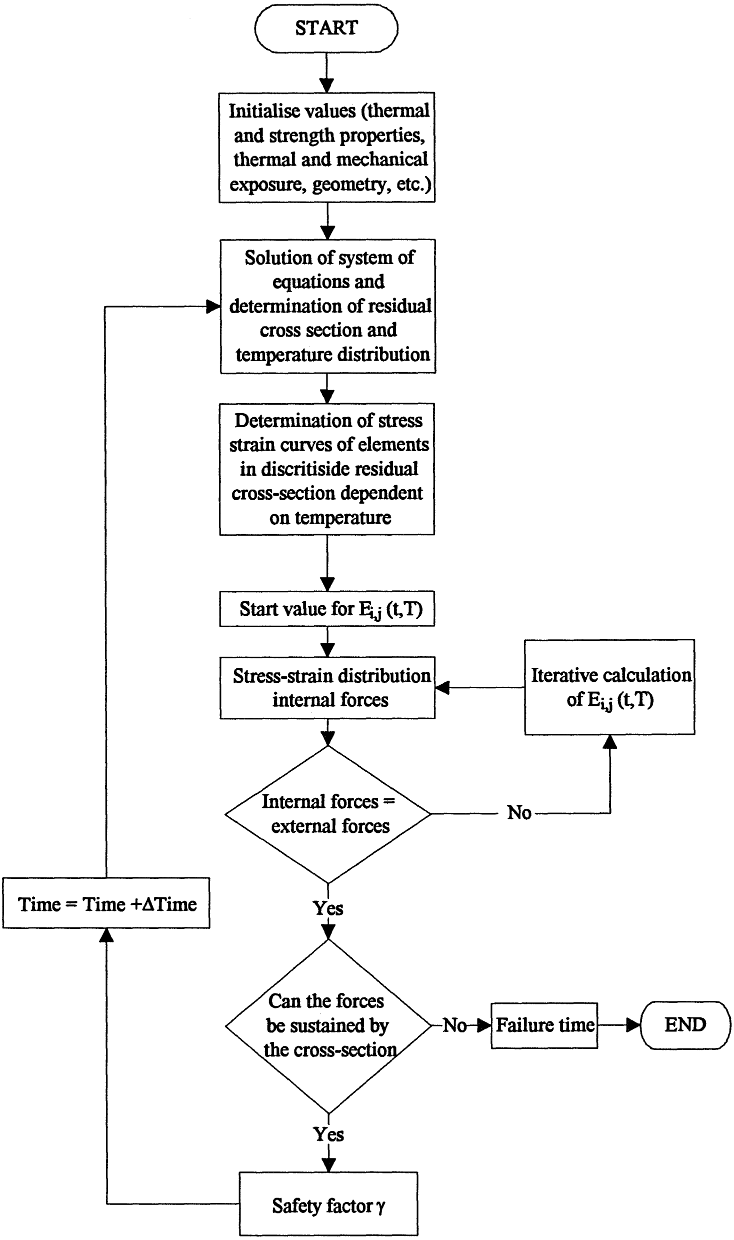

FIGURE 9. Calculation procedure flowchart

CONCLUSIONS

The theoretical basis of a numerical model for realistic calculation of fire resistance time of timber elements is described. Thermal analysis is based on transient heat and mass transfer in cross-section exposed to fire. The model includes geometrical and physical non-linearities. Individual values of strength, density, moisture content, geometry (the cross-section area, slenderness), thermal and mechanical exposure etc. can be used as input data. The comparison of calculated results with those measured in fire tests shows good agreement. The model can be applied for standard fire conditions and for natural fires.

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