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DIVISION OF BUILDING FIRE SAFETY AND TECHNOLOGY
REPORT LUTVDG/(TVBB - 3010)

OVE PETTERSSON - ROBERT JÖNSSON

FIRE DESIGN OF WOODEN STRUCTURES

LUND 1983

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LUND 1983

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FIRE DESIGN OF WOODEN STRUCTURES

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1 INTRODUCTION

An analytical prediction of the real fire behaviour of a wooden structure requires access to functionally valid models, describing the relevant physical processes with respect to exposure and structural response. Compared with structures of other types of material as steel and concrete, wooden structures then cause special difficulties due to their combustibility and char-forming properties.

The prediction of the behaviour of a structure in any situation - normal or accidental - is always associated with uncertainties. The physical models exhibit uncertainties in consequence of their schematization - model uncertainties. The influence variables included in the physical models exhibit uncertainties with respect to their numerical values attained in the individual case - stochastic uncertainties.

The only consistent method available for dealing with these uncertainties in a prediction of the real behaviour of a structure is a probability based design with specified safety factors. The effect of the various uncertainties and the required level of structural reliability then decide the values of these safety factors.

The level of structural reliability reflects the acceptable risk with respect to the attainment of a defined limit state, for instance, the ultimate load bearing capacity. This risk is related to

- * the probability of occurrence of a severe fire - depending on the compartmentation, the fire brigade actions and an installed fire extinguishment system, if any, and
- * the consequences of a structural failure - depending on such influences as the occupancy, the height and volume of the building and the importance of the structure or structural member to the overall stability of the building.

In the light of the principles outlined, the state of the art is briefly described and exemplified below regarding an analytical fire design of wooden structures, based on the natural compartment fire exposure. The examples given are limited to load bearing laminated timber structures.

2 LIMIT STATE CONDITION

Generally the design criterion in a fire design requires that no limit state is reached during the fire exposure. Depending on the type of practical application, the design criterion can be required to apply with either the complete fire process or a limited part of it, determined from the time necessary for the fire brigade to attack the fire successfully under the most severe conditions or from the evacuation time for the building.

In the design, one, two or all of the following limit state conditions apply:

- * limit state with respect to load bearing capacity,
- * limit state with respect to insulation,

* limit state with respect to integrity.

For a load bearing structure, the design criterion implies that the minimum value of the load bearing capacity $R(t)$ during the fire exposure shall meet the load effect on the structure S , i.e. - Fig. 1a

$$\min\{R(t)\} - S \geq 0 \quad (2.1)$$

The criterion must be fulfilled for all relevant types of failure - bending failure, shear failure, torsion failure, instability failure, etc.

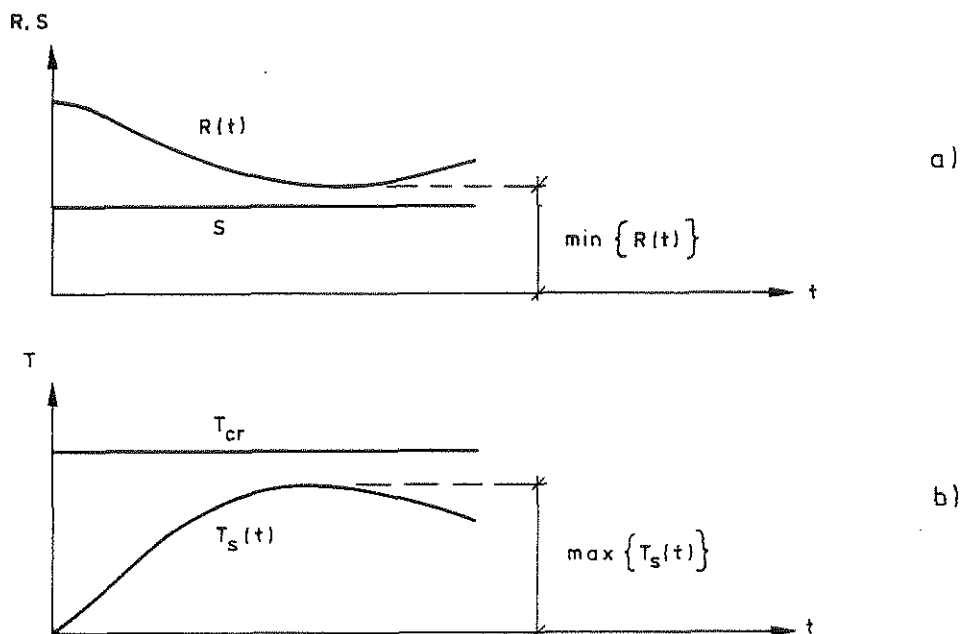


Figure 1. Design criteria with respect to load bearing capacity (a) and insulation (b)

For a separating structure, the design criterion with respect to insulation can be formulated analogously as - Fig. 1b

$$T_{cr} - \max\{T_s(t)\} \geq 0 \quad (2.2)$$

where

T_{cr} = maximum temperature of the unexposed side of the separating structure, acceptable with respect to the requirement to prevent a fire spread from the fire compartment to an adjacent compartment,

$T_s(t)$ = highest temperature on the unexposed side of the separating structure at time t of the relevant fire process.

For the requirement with respect to integrity, which can be decisive for some types of separating elements, there is no analytically expressed design criterion available at present.

3 PHYSICAL MODEL AND RELATED FIRE EXPOSURE

The physical model for an analytical fire design of a load bearing wooden structure, exposed to a natural compartment fire, is shown summarily in Fig. 2.

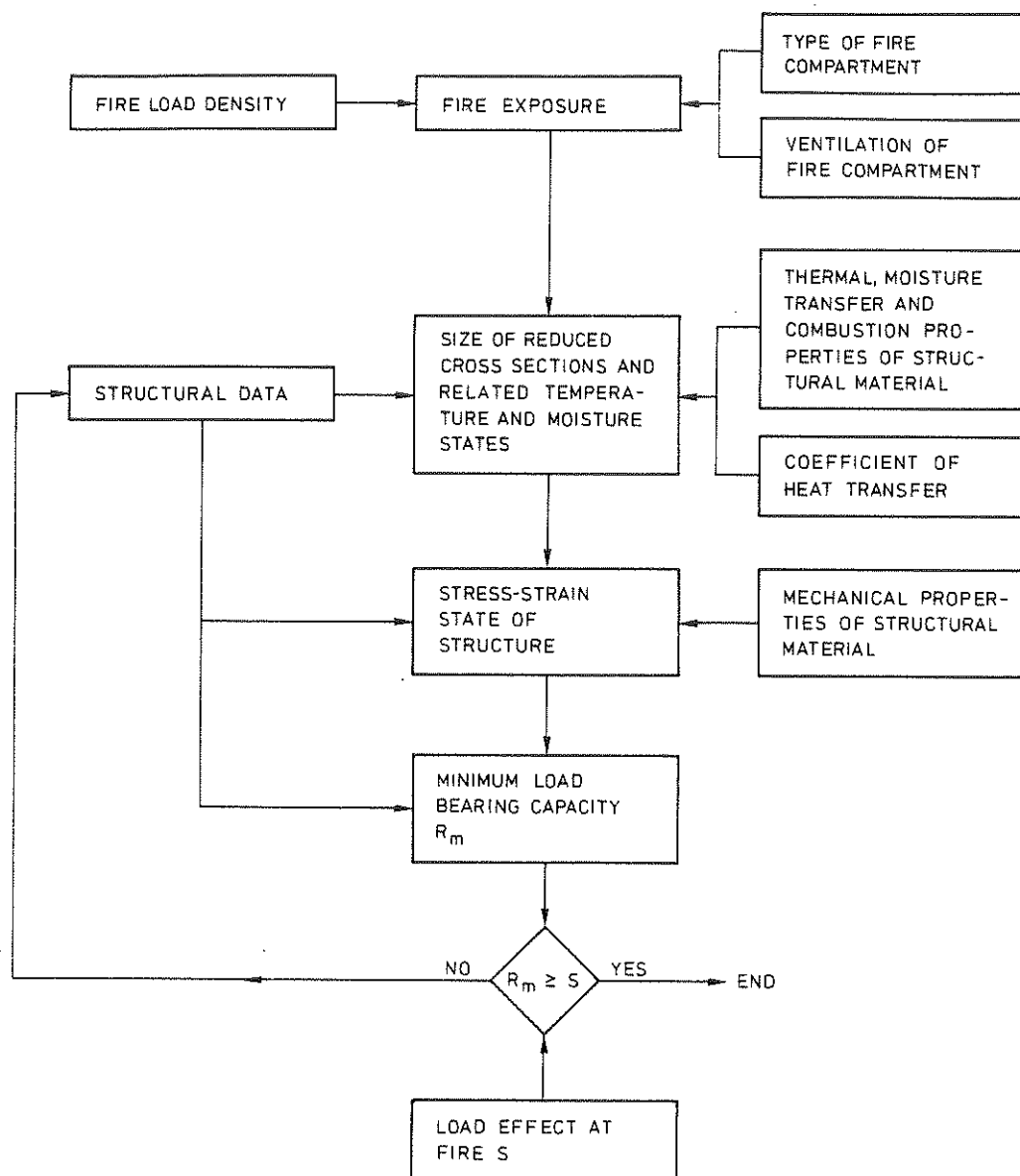


Figure 2. Physical model for an analytical fire engineering design of load bearing wooden structures, exposed to a natural compartment fire

The design procedure starts by a determination of the fire exposure, given by, for instance, the gas temperature-time curve of the natural compartment fire. In the individual practical application, the fire exposure then can be obtained either by heat and mass balance calculations for the fire compartment - cf. [1] - [9] - or directly from a systematized design basis of the type exemplified by Fig. 3 [3], [7]. The amount and combustion characteristics of the fire load and the geometrical, ventilation and thermal properties of the fire compartment are the decisive influences.

The gas temperature-time curves T_t-t in Fig. 3 apply to a fire compartment with surrounding structures, made of a material with a thermal conductivity $\lambda = 0.81 \text{ W} \cdot \text{m}^{-1} \cdot \text{OC}^{-1}$ and a heat capacity $\rho c_p = 1.67 \text{ MJ} \cdot \text{m}^{-3} \cdot \text{OC}^{-1}$ - fire compartment, type A. Such a surrounding material roughly corresponds to an average of brick, concrete, and aerated concrete. For fire compartments with surrounding structures, whose thermal properties deviate from fire compartment type A, the actual fire process can be transferred to a gas temperature-time curve for fire compartment type A by using an effective fire load density q_{tf}

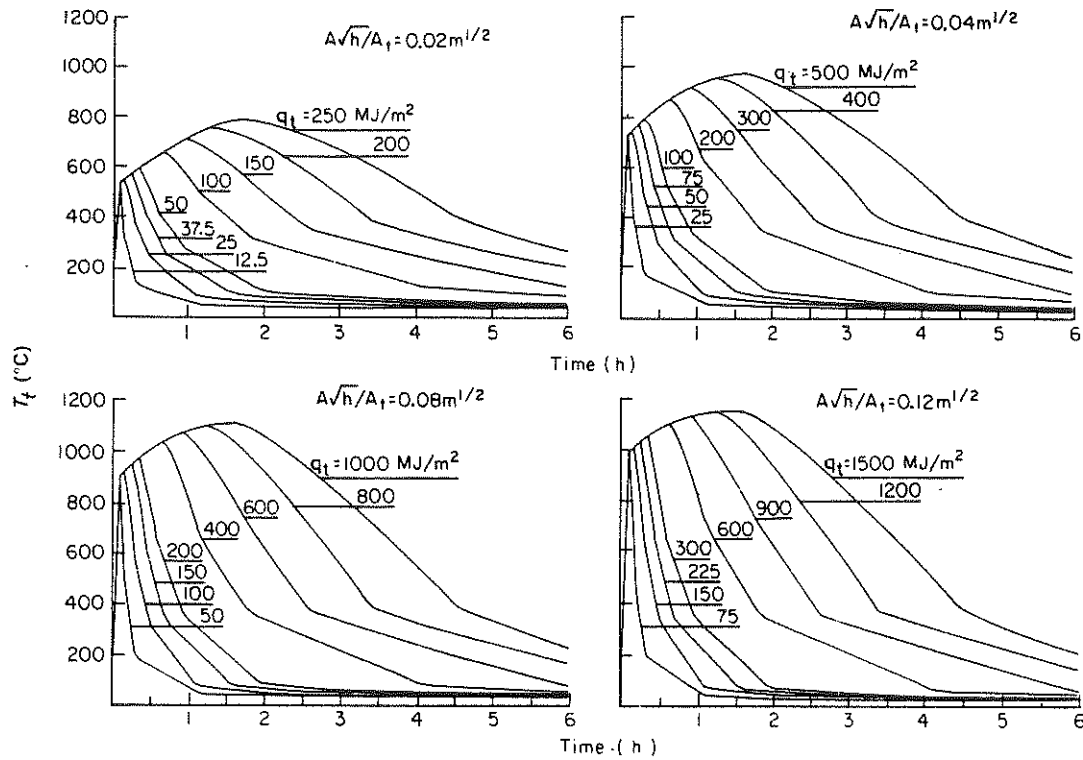


Figure 3. Gas temperature-time curves for a complete, fully developed compartment fire with varying values for the fire load density q_t - Eq. (3.2) - and the opening factor $A\sqrt{h}/A_t$. A is the total opening area of the fire compartment, h is a weighted mean value of the height of the openings based on their size, and A_t is the total internal surrounding area of the fire compartment, including openings. Fire compartment, type A [3], [7]

and an effective opening factor $(A\sqrt{h}/A_t)_f$, calculated from the real fire load density q_t and the real opening factor $A\sqrt{h}/A_t$ according to the formulae:

$$q_{tf} = K_f q_t ; (A\sqrt{h}/A_t)_f = K_f A\sqrt{h}/A_t \quad (3.1)$$

In [7], [10], [11], the coefficient K_f is given for seven types of fire compartments, defined by their surrounding structures.

The fire load density q_t is given by the relationship:

$$q_t = \frac{1}{A_t} \sum \mu_v m_v H_v \quad (\text{MJ} \cdot \text{m}^{-2}) \quad (3.2)$$

where

m_v = total mass of combustible material v (kg),

H_v = calorific value of combustible material v ($\text{MJ} \cdot \text{kg}^{-1}$),

μ_v = fraction between 0 and 1, giving the real degree of combustion for each component v of the fire load,

A_t = total interior area of the surfaces bounding the fire compartment, openings included (m^2).

In the opening factor $A\sqrt{h}/A_t$ of the fire compartment

A = total area of door and window openings (m^2),

h = mean value of the heights of the openings, weighted with respect to each individual opening area (m).

The gas temperature-time curves according to Fig. 3 are applicable to fire compartments of a size representative of dwellings, ordinary offices, schools, hospitals, hotels, and libraries. For fire compartments with a very large volume - for instance, industrial buildings and sports halls - the curves give an unsatisfactory description of the real fire exposure. At present, there is no validated design basis available for the determination of the fire exposure in compartments with a very large volume.

Returning to the physical model as shown in Fig. 2, in the next step, the fire exposure is transferred analytically to the time variation of the size of the unburnt cross sections of the structure and their temperature and moisture states. Input variables are the structural data, the coefficients of heat transfer for the various surfaces of the structure and the thermal, moisture transfer, combustion and char-forming properties of the structural material. With information on the mechanical properties of the structural material as function of the temperature and moisture content as further input data, then a determination has to be done of the transient stress-strain state and the corresponding time variation of the load bearing capacity of the structure $R(t)$.

A comparison between the minimum value R_m of the load bearing capacity $R(t)$ during the relevant fire process and the load effect at fire S finally decides whether the structure can fulfil its required function or not during the fire exposure, as specified by the limit state condition according to Eq. (2.1).

For a separating structure, the physical model gives the transient temperature state, defining the maximum value of the highest temperature on the unexposed side of the structure $\max\{T_s(t)\}$ during the relevant fire process. The corresponding limit state condition follows Eq. (2.2) with respect to the required function of insulation. The supplementary limit state condition regarding the integrity function has to be proved experimentally, when required, in either a fire resistance test or a simplified small scale test.

4 PROBABILITY BASED DESIGN

The modern development of functionally well-defined, analytical structural fire design methods includes a probabilistic approach, based either on a system of partial safety factors or on the safety index concept [12] - [19].

For the probabilistic model to be integrated with the physical model, various levels can be distinguished:

- * an exact evaluation of the failure probability $P(R < S)$, using multi-dimensional integration or Monte Carlo simulation,
- * an approximate evaluation of the failure probability $P(R < S)$, based on first order reliability methods (FORM), and
- * a practical design format calculation, based on partial safety factors and taking into account characteristic values for action effects and response capacities.

For practical purposes, an exact evaluation of failure probability is not possible. Also the FORM approximations are too cumbersome for everyday design and the more simplified practical design formats have to be used.

The probabilistic influences are then taken into account by specifying characteristic values and related partial safety factors for - cf. Fig. 2 - the fire load density, such structural design data as imperfections, the thermal, moisture transfer, combustion and char-forming properties, the mechanical properties and the loading. For each quantity, the characteristic value and the partial safety factor define a design value as exemplified by Fig. 4 for the loading and mechanical strength and by Table 1 for the fire load density. The design procedure ends up by a design value of the load bearing capacity of the structure R_d for the relevant fire process, which has to meet the design load effect at fire S_d , i.e.

$$R_d - S_d \geq 0 \quad (4.1)$$

Depending on the type of practical application, the requirement (4.1) then has to be verified for either the complete fire process or a limited part of it, determined by the time necessary for the fire brigade to attack the fire successfully under the most severe conditions or by the design evacuation time for the building.

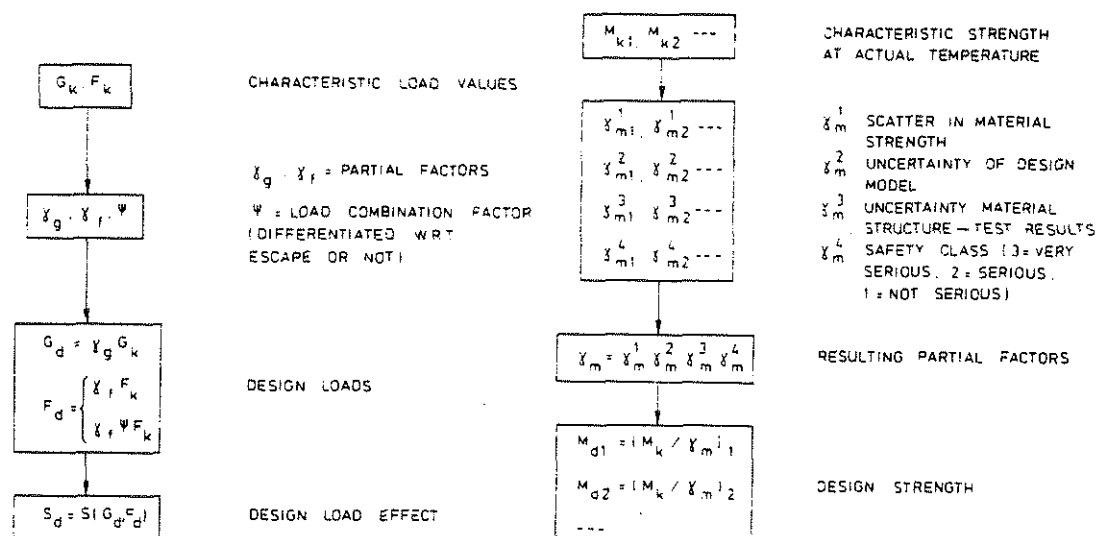


Figure 4. Determination of design load effect S_d and design strength M_d from characteristic values and related partial safety factors γ

The partial safety factors are to be derived by a probabilistic analysis, based on a first order reliability method (FORM), with the following probabilistic effects taken into consideration:

- * the uncertainty in specifying the fire load density,
- * the uncertainty in specifying the ventilation characteristics of the fire compartment and the thermal properties of the structures surrounding the fire compartment,

- * the uncertainty of the analytical model for the determination of the compartment fire and its thermal exposure on the structure,
- * the uncertainty in specifying the design data of the structure, dimensions, imperfections, etc.,
- * the uncertainty in specifying the thermal, moisture transfer, combustion, char-forming and mechanical properties of the structural material,
- * the uncertainties of the analytical models for the calculation of the reduced cross sections of the structure and the related transient temperature and moisture states,
- * the uncertainties in the analytical models for the calculation of the transient stress-strain state and the ultimate load bearing capacity of the structure,
- * the uncertainty in specifying the loads,
- * the uncertainty of the analytical model, describing the load effect on the structure,
- * the probability of occurrence of a severe compartment fire,
- * the efficiency of the fire brigade actions,
- * the effect of an installed extinction system, and
- * the consequences of a structural failure.

For the detailed procedure of deriving the partial safety factors, reference is given to [19].

Category of structural member	Design fire load density q_d	Duration of fire exposure
K0	-	-
K1	$1.0 q_k$	≤ 30 min
K2	$1.0 q_k$	complete fire process
K3	$1.5 q_k$	complete fire process

Table 1. Design fire exposure, expressed by design fire load density q_d and duration of fire exposure. q_k is the characteristic value of the fire load density

As indicated in the introduction, the functional requirements to be laid down for the fire engineering design should be differentiated with respect to such aspects as the occupancy, the height and volume of the building, and the importance of the structure or structural member to the overall stability of the building. This can be considered by, for instance, a system of safety classes with allocated failure probabilities and related γ_m -values of the partial safety factors, affecting the design strength M_d - cf. Fig. 4 and [13]. The effect of the probability of occurrence of a severe compartment fire, the fire brigade actions and an installed fire extinguishment system, if any, can be accounted for principally in the same way. An alternative solution is to include these influences in the determination of the design fire load density q_d and the design fire exposure. This latter way is chosen in a Swedish probability based design method, [15], [16], [20], by dividing the structures or structural members

into categories with a related differentiation of the design fire load density q_d and the length of the fire process to be considered in the design - Table 1. The characteristic fire load density q_k then is defined as the value corresponding to a probability of excess of 20%. The related gas temperature-time curves of the fire exposure are specified in accordance to Fig. 3 as a function of the effective fire load density $q_{t,f}$ and the effective opening factor of the fire compartment $(A\sqrt{h}/A_t)_f$.

In the present version of the Swedish design method, the presence of an approved sprinkler system is taken into account only in a rough way by a transfer of the structure or structural member to the next lower category.

Consequently, the partial safety factor γ_m^4 in the determination of the design strength M_d according to Fig. 4 is to be made equal to 1 in the Swedish design method.

5 THERMAL AND MECHANICAL RESPONSE

5.1 Rate of Charring. Transient Temperature and Moisture States

For a practical determination of the transient temperature state of fire exposed structures, numerical methods have been developed and arranged for computer calculations. The methods are based either on finite difference or finite element approximations.

In an application of a finite difference method, the structure is divided into elements and for each one of these, a heat balance equation is set up in the form of a difference equation, approximating the differential heat balance equation. The mass of each element is assumed as concentrated at its centre. For the total structure, then a system of equations is obtained which can be solved for the temperatures of these element centres by stepwise integration.

In the finite element method of analysis, the structure is idealized by an assemblage of discrete elements. The elements may be of variable size and shape and connected at a finite number of nodal points. Within each element, the temperature field is approximated by a set of interpolation or shape functions, defining the temperature uniquely in terms of the nodal temperatures of the element.

The analysis is based on the heat balance equilibrium equation for transient heat conduction in matrix form, based on the FOURIER law

$$\underline{\nabla}^T (\underline{\lambda} \underline{\nabla} T) - \dot{\epsilon} + Q = 0 \quad (5.1)$$

where

T = temperature,

$\underline{\lambda}$ = symmetric positive definite thermal conductivity matrix,

$\dot{\epsilon} = \partial e / \partial t$ = rate of specific volumetric enthalpy change,

Q = rate of internally generated heat per unit volume,

t = time.

The gradient operator $\underline{\nabla}$ is defined as

$$\underline{\nabla} = \begin{bmatrix} \frac{\partial}{\partial x} \\ \frac{\partial}{\partial y} \\ \frac{\partial}{\partial z} \end{bmatrix} \quad (5.2)$$

where x , y and z are Cartesian coordinates.

A solution of Eq. (5.1) requires the initial and boundary conditions to be specified. The initial condition is given by the temperature distribution within the structure at a reference time zero. The boundary conditions are prescribed as temperature $T = T(x, y, z, t)$ or heat flow q on parts of the boundary ∂V_T and ∂V_q , respectively. The total boundary is then

$$\partial V = \partial V_T + \partial V_q \quad (5.3)$$

Written in matrix form, the heat balance equilibrium equation for transient heat conduction reads [21]

$$\underline{K}\underline{T} + \frac{\partial}{\partial t}(\underline{C}\underline{T}) = \underline{F} = \underline{F}_Q + \underline{F}_q \quad (5.4)$$

where

\underline{K} = heat conductivity matrix,

\underline{T} = vector of nodal temperatures,

\underline{C} = nominal heat capacity matrix,

\underline{F}_Q = vector of rate of internally generated heat per unit volume,

\underline{F}_q = vector of rate of heat flow supplied at the boundary.

Alternatively, the heat balance equation can be expressed in terms of the nodal enthalpy vector \underline{E} instead of the temperature vector \underline{T} , i.e.

$$\underline{K}^*\underline{E} + \frac{\partial}{\partial t}(\underline{E}) = \underline{F} \quad (5.5)$$

where

$$\underline{K}^* = \underline{K}\underline{C}^{-1} \quad (5.6)$$

Eq. (5.4) or (5.5) can be solved by a direct step-by-step integration, using either a forward-, mid- or backward-difference method. Regard has to be paid to the fact that the heat conductivity matrix \underline{K} and the heat capacity matrix \underline{C} depend on the temperature T to an extent that cannot be disregarded. Further complications arise when the material undergoes phase changes during the heating and when the material has an initial moisture content.

As concerns the finite element computer programs developed for a direct application to a structural fire design, FIRES-T [22] and FIRES-T3 [23] make use of an implicit backward-difference time integration scheme while TASEF-2 [21] is an explicit forward-difference method.

Fire exposed wooden structures and structural members present special difficulties with respect to a calculation of their thermal response due to the continuous charring and related decrease of the effective cross section by combustion of the material. To that has to be added, that the heat transfer in a wooden structure at fire as a rule is combined with a considerable moisture transport and from a strict thermodynamical point of view, these two transport mechanisms should be analysed simultaneously by a system of related partial differential equations, arranged for numerical solutions. Experiments, conducted to characterize the transient moisture gradients in wood slabs subjected to fire on one face, indicate an average peak moisture content in various sections of up to 2 times greater than the initial moisture content [24].

Analytical models for a calculation of the charring rate and depth of wood at varying thermal exposure are presented in, for instance, [25] - [28].

In [28], more than 100 tests are reported, carried out for a determination of the charring depth at varying thermal exposure. An analytical model for the charring of wood is set up, consisting of five sub-models describing different processes. The model is used for checking against the test results and for a calculation of design diagrams giving directly the charring depth of a cross section at a natural compartment fire exposure, defined by the gas temperature-time curves according to Fig. 3. The diagrams apply to structures and structural members of glued laminated timber. A curve fitting of the charring diagrams results in the following approximate formulae for a calculation of the charring depth β (mm) [28]:

$$\theta = \frac{0.0175q_t}{\frac{A\sqrt{h}}{A_t}} \quad (5.7)$$

$$\beta_o = 1.25 - \frac{0.035}{\frac{A\sqrt{h}}{A_t} + 0.021} \quad (5.8)$$

$$\left. \begin{aligned} \beta &= \beta_o t & \text{for } 0 \leq t \leq \frac{\theta}{3} \\ \beta &= \beta_o \left(-\frac{1}{12}\theta + \frac{3}{2}t - \frac{3t^2}{4\theta} \right) & \text{for } \frac{\theta}{3} \leq t \leq \theta \end{aligned} \right\} \quad (5.9)$$

where

q_t = fire load density, per unit area of bounding surfaces (MJ \cdot m $^{-2}$) - Eq. (3.2),

$A\sqrt{h}/A_t$ = opening factor of the fire compartment (m $^{\frac{1}{2}}$),

θ = time, at which maximum charring is reached for the values of q_t and $A\sqrt{h}/A_t$ in question (minutes),

β_o = initial value of rate of charring (mm \cdot minute $^{-1}$),

t = time (minutes).

The model derived in [28] does not give any information on the temperature and moisture distribution within the un-charred part of the cross section. A charring model, which includes a determination of the related temperature distribution, is presented in [27] on the condition of oven-dried wood. The model of wood pyrolysis, derived in [26], is more general and indicates also approximate methods for a calculation of the temperature as well as moisture distribution within the reduced effective cross section of the structure. A further development of the model is, however, required for making it easily applicable in practice.

5.2 Mechanical Properties and Structural Behaviour

A transformation of the transient temperature and moisture states within the un-charred part of the cross sections of a fire exposed wooden structure to the structural behaviour and load bearing capacity requires validated analytical models for the mechanical behaviour of the structural material in the temperature and moisture ranges associated with fires.

For wooden structures, the present state of knowledge is far less ad-

vanced than for steel and concrete structures as concerns an analytical modelling of the transient stress-deformation behaviour at a fire exposure. The available information on the mechanical properties of wood is mainly based on results of tests with small specimens, free from material imperfections. For the bending strength, it has been shown that the stresses in the compression zone are decisive for perfect small test specimens while the stresses in the tension zone initiate the failure for structural members of ordinary size. From a probabilistic point of view, the strength of wood follows a Gaussian normal distribution for small test specimens while the strength distribution for ordinary structural members is of an extreme value type according to Weibull, verifying a brittle failure as decisive.

A comprehensive information is available concerning the compression strength, tensile strength, bending strength, shear strength, modulus of elasticity and shear modulus, parallel to and perpendicular to the grain, determined from tests with small specimens conditioned to different combinations of temperature and moisture content. An excellent survey of the information is given in [29], from which Figs. 5 and 6 are reproduced. The relatively large scatter in the test results is due to the influence of various wood species and the difficulties of measuring combined temperature and moisture states.

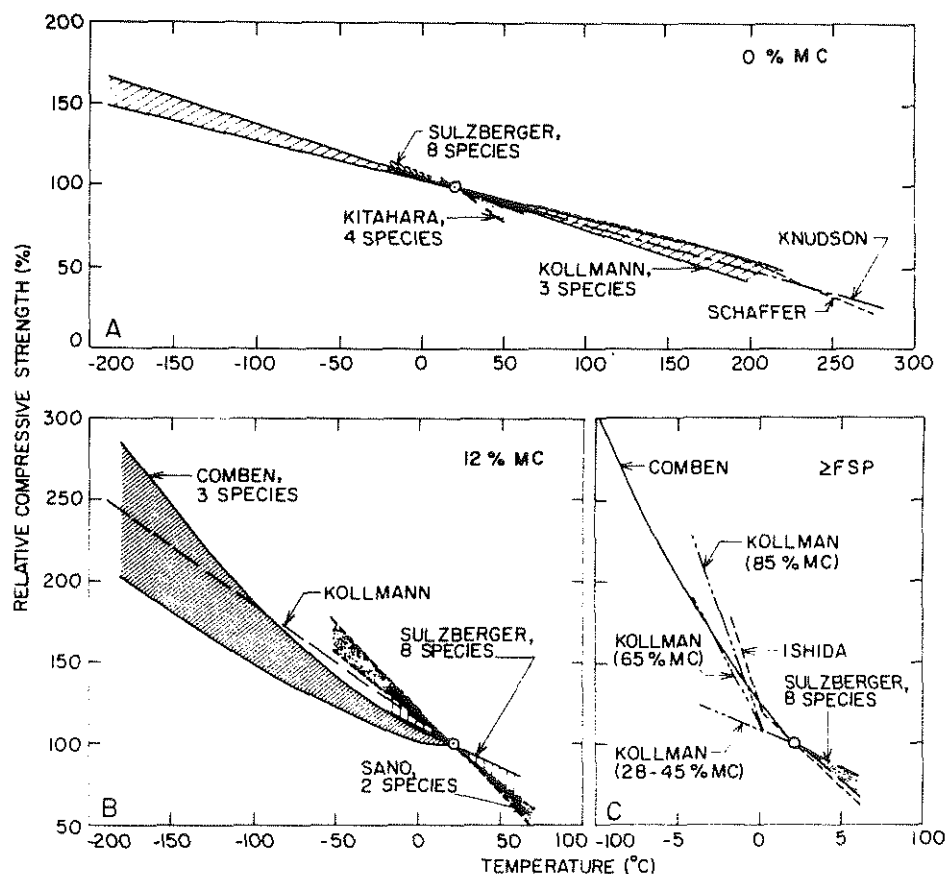


Figure 5. Effect of temperature on compressive strength of wood parallel-to-the-grain. 100% at 20°C. A: 0% moisture content (MC), B: ~12% MC, C: ≥ fiber saturation point (FSP, ~30% MC) [29]

Based on results of experiments on small test specimens, some rough analytical models have been developed for the mechanical behaviour of wood in relation to fire exposure. However, there is no validated analytical model available for the mechanical behaviour which can be applied for a description of the deformation process at simultaneous

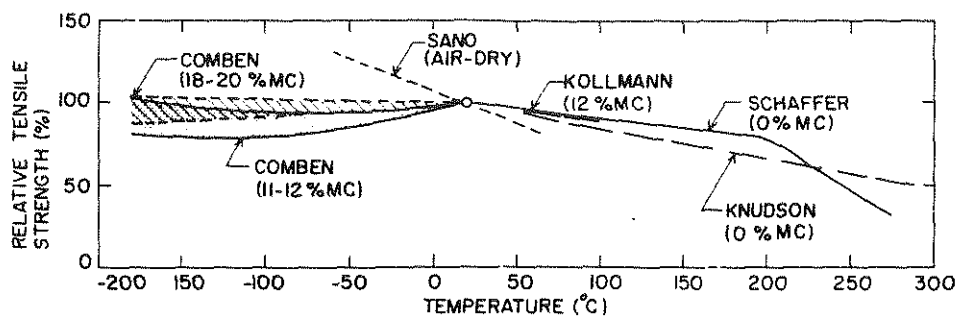


Figure 6. Effect of temperature on tensile strength of wood parallel-to-the-grain. 100% at 20°C. MC = moisture content [29]

transient states of stress, temperature and moisture. The conditions prevent a reliable calculation of the deflections of fire exposed wooden structures to be performed and limit a structural fire design primarily to a determination of the ultimate load bearing capacity. The lack of practically adaptable model for a calculation of the moisture gradient in the un-charred part of the cross section then requires a relatively rough approximation to be introduced at the estimation of the decrease in the ultimate bending moment of the reduced cross section due to increased temperature and moisture content during the fire. As a rule, this decrease is taken into account by multiplying the ultimate bending stress at normal temperature by a reduction coefficient μ with a value giving results on the safe side.

5.2.1 Laminated Timber Beams

With the charring depth β calculated according to Eqs. (5.7) - (5.9), the ultimate load bearing capacity of a rectangular, laminated timber beam, fire exposed on three or four sides, can easily be determined by applying the design diagrams in Figs. 7 and 8 [7], [30], [31]. The design diagrams give the relationship between the charring depth β , the width B and the height D of the cross section, and the quotient K between the load of failure at normal temperature and the design load at fire - the safety factor. The relationship is valid on the assumption of a bending failure. The reduction factor μ is roughly put equal to 0.8. For $\beta/B > 0.25$, the curves are dash marked since the assumptions for the calculation of the charring depth are insufficiently experimentally verified within this region.

For slender beams with small lateral flexural rigidity and/or torsional rigidity, the risk of lateral buckling can be decisive in a structural design. In a fire, this risk is continuously increased since the width/height ratio B/D of the beam decreases by the charring. The risk will be further strengthened if intermediate supports of the beam fail during the fire exposure.

A comprehensive design aid for fire exposed rectangular, laminated timber beams with respect to lateral buckling is presented in [33]. The design aid is exemplified by Fig. 9 which gives the relationship between the charring depth β , the width B and the height D of the cross section, the safety factor K and a lateral buckling parameter

$$\eta = \sqrt{\frac{LD}{mB^2}} \quad (5.10)$$

where L is the length of the span and m a coefficient in the formulas

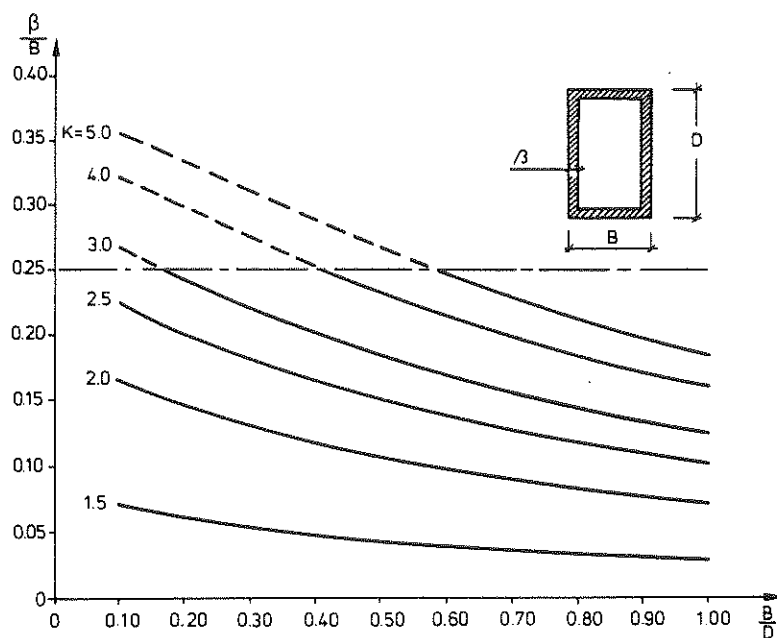


Figure 7. Ratio β/B as a function of width-height ratio B/D and safety factor K for a rectangular, laminated timber beam, fire exposed on four sides

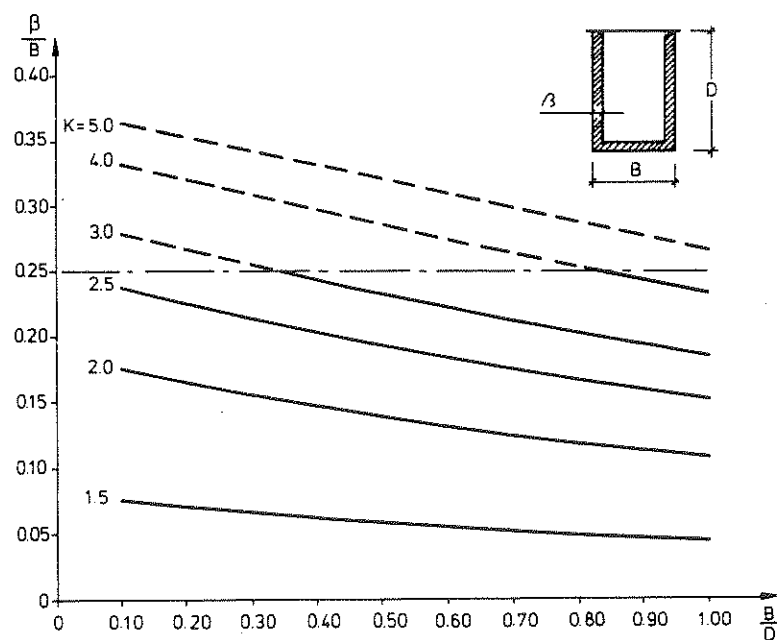


Figure 8. Ratio β/B as a function of width-height ratio B/D and safety factor K for a rectangular, laminated timber beam, fire exposed on three sides

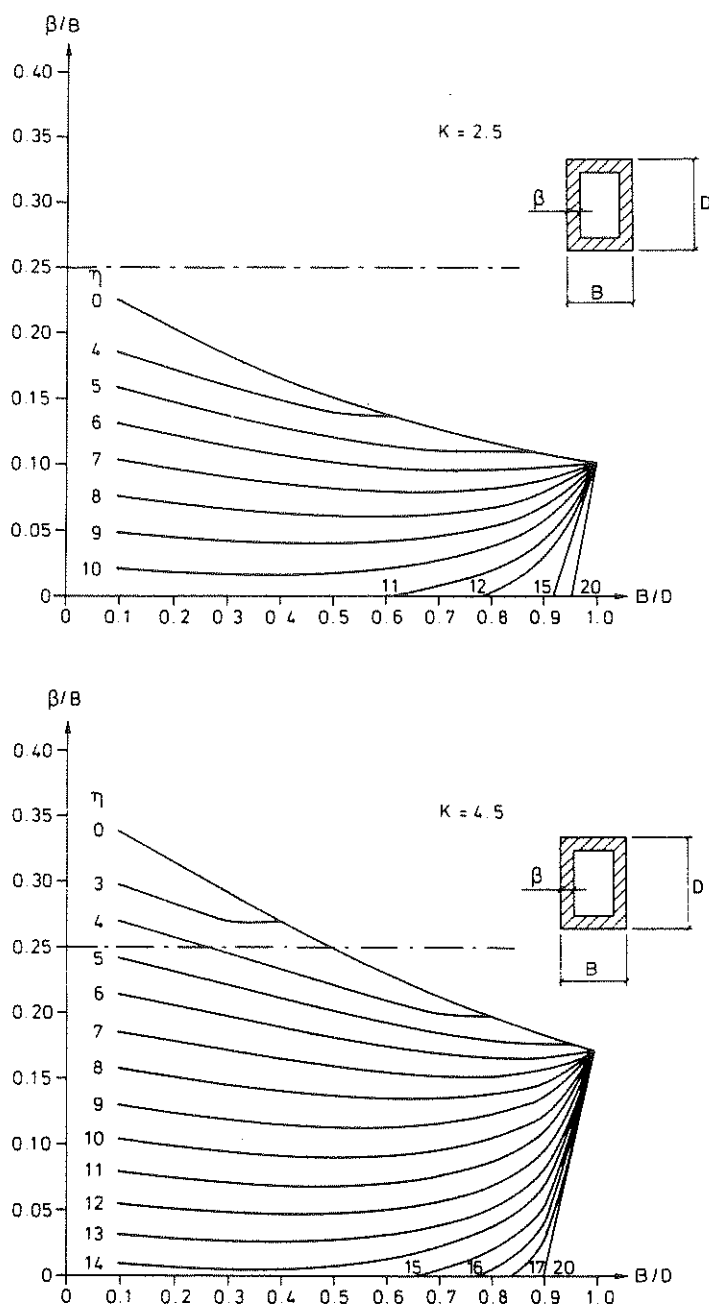


Figure 9. Ratio β/B as a function of the width-height ratio B/D and the lateral buckling parameter η , given by Eq. (5.10), for two different values of the safety factor K . Rectangular, laminated timber beam, fire exposed on four sides

for the elastic, critical load with respect to lateral buckling:

$$\left. \begin{array}{l} M_{cr} \\ P_{cr} L \\ q_{cr} L^2 \end{array} \right\} = m \frac{\sqrt{B_y C}}{L} \quad (5.11)$$

M_{cr} , P_{cr} and q_{cr} are the critical bending moment, concentrated load and distributed load, respectively, B_y the lateral flexural rigidity and C the torsional rigidity of the cross section. The coefficient m depends on the load and support conditions and can be found for most practical applications in standard textbooks and manuals. K is

the safety factor against failure in bending for the actual loading before fire.

5.2.2 Laminated Timber Columns

A structural fire design of axially compressed columns with negligible risk of buckling follows the same procedure as a fire design of beams. If the buckling risk is decisive, the problem is complicated by the continuous decrease of the buckling load during the fire due to the reduction of the effective cross section and the related increase of the slenderness ratio.

A design method, easily applicable in practice, is presented in, for instance, [7], [31]. Fig. 10 exemplifies the appurtenant design aid by two diagrams, giving the relationship between the charring depth β , the initial slenderness ratio λ_0 and the quotient p between the design load at fire and the permissible load at normal temperature. The diagrams apply to a column with a square cross section, fire exposed on four sides, and a column with a rectangular cross section, located in such a way that only two opposite sides are fire exposed, respectively. In the latter case, the column is assumed to deflect at buckling in a direction perpendicular to the fire exposed sides.

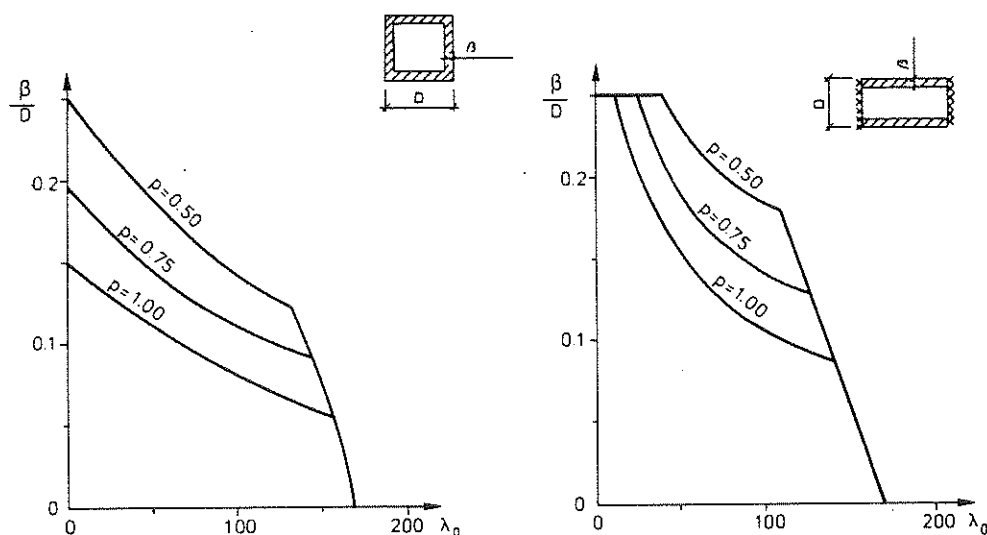


Figure 10. Ratio β/D as a function of the initial slenderness ratio λ_0 and the quotient p between the actual load at fire and the permissible load at normal temperature. Laminated timber columns, fire exposed on four sides (left figure) and on two opposite sides (right figure), respectively

6 SUMMARY

The paper describes and discusses the state of the art concerning the possibilities of an analytical prediction of the real fire behaviour of wooden structures and structural members. The principles of a probability based design are outlined with reference to a physical model according to Fig. 2, connected to a natural compartment fire exposure. The design procedure is exemplified by a Swedish method, based on a practical design format calculation, specifying characteristic values and partial safety factors for the action effects and response capacities. The model and stochastic uncertainties, to be included in the derivation of the partial safety factors, are listed. In the method,

the consequences of a structural failure and the effects of the probability of a severe compartment fire, the fire brigade actions and an installed fire extinguishment system, if any, are approximately accounted for by dividing the structures or structural members into categories with a related differentiation of the design fire load density and the length of the fire process to be considered in the design.

The state of knowledge on the thermal and mechanical response of fire exposed wooden structures is reviewed with respect to the rate of charring at varying thermal exposure and the related temperature and moisture gradients in the un-charred part of the cross section, the mechanical properties of wood at a simultaneous increase of temperature and moisture content, and the fire behaviour and ultimate load bearing capacity of the structure. The available design aid is exemplified, focusing on laminated timber structures. Design diagrams are given for a determination of the ultimate load bearing capacity of beams with respect to bending and lateral buckling and of the buckling load for columns.

The lack of validated, practically adaptable, analytical models for the transient temperature and moisture states within the un-charred part of the cross section and for the mechanical behaviour of the material at simultaneous transient states of stress, temperature and moisture is emphasized. The conditions prevent a reliable calculation of the deflections of fire exposed wooden structures to be performed at present and limit a structural fire design primarily to a determination of the ultimate load bearing capacity.

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