Timber structures and fire : a review of the existing state of knowledge and research requirements

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FOREWORD

Wood is a renewable natural material which has a long tradition in building technology. From the point of view of energy, it is superior to non-renewable building materials. The energy consumed in producing wood, for instance, is only about 10% of that in producing steel. Wood causes far less damage to the environment than most other building materials, and residual products from wood processing amount to only between a quarter and a half of corresponding residual products from mining and mineral processing.

About one half of Swedish wood production is utilised in prefabricated houses, building components and glued laminated timber - and to a dominant extent in different types of loadbearing and separating constructions and cladding materials. To this must be added a production share for building joinery, amounting to about 15%.

Traditionally, wood and wood-based products have been used to a large extent for private dwellinghouses, and at present about 90% of private dwellinghouses in Sweden are made of timber. Up to about 20 years ago the method of construction was relatively uniform, with the building frame made in the form of a stud system in loose and pre-cut timber, and, in some cases, prefabricated wall blocks, often erected without any internal cladding or insulation.

In recent decades the methods of building private dwellinghouses have increased in number in step with the increased prefabrication of frame systems, and at present there are about ten system groups ranging from pre-cut timber to room units. The trend appears to be towards a further increase in the number of systems.

Changed conditions relating to construction - primarily problems relating to energy and the shortage of trained labour on the construction sites - have provided the initiative for new lines of development for buildings and building components of which wood and wood-based products form a part. Examples of these are thin and composite structural elements of timber, composite construction comprising timber and metal sheeting as loadbearing elements, and sandwich construction comprising loadbearing wood-based boards with an infill of foamed plastics.

Wood and wood-based products, especially glued laminated timber and sandwich units, are also well suited for different types of larger structures for large-span and multistorey buildings, etc. However, in Sweden timber is not a traditional material in this field, and there is only limited experience available. In countries such as Canada, Switzerland, Germany and USA, on the other hand, wood and wood-based products are used to a conlarge-span industrial, sports and exhibition buildings, multistorey buildings of up to five storeys, churches and bridges on rural roads.

Timber construction technology was for a long time an area in which little research was done, and the amount of expenditure on research was of very small extent compared with that relating to steel and concrete construction. Recently, however, the Swedish Board for Technical Development (STU), together with the timber industry, came to a decision to allocate considerable funds for timber research and development over a five year period, and timber construction technology was considered to be one of the subject areas in which development of capability and expansion of knowledge were important. Two programme proposals, namely JOHANESSON, C M, "Timber construction technology - research and development needs", STU Information Bulletin No 207/1981, and GIRHAMMAR, U A, "Large-span buildings of timber - research and development in the field of large timber structures", STU Information Bulletin No 293/1982, have been drawn up by commission of STU to provide the background to this work. The object of these publications is to initiate projects and to serve as the basis for the planning of research in the field of timber construction.

It is essential that fire protection should be given a central place in future timber construction research. This is emphasised in the national collective fire research programme for 1982-84 which has been drawn up by the Swedish Board for Fire Research (BRANDFORSK). In order that a planning instrument may be created for such nationally integrated fire research, BRANDFORSK has commissioned the Division of Building Fire Safety and Technology at Lund Institute of Technology to produce a research programme for the subject area timber structures and fire.

This report presents such a programme against the background of a brief review of existing knowledge in this area. Chapter 1 examines design methods and related performance requirements and criteria against an international present state and development perspective, and draws certain conclusions regarding urgent research projects of an overriding character. Chapters 2-7 give corresponding reviews of the state of the art in relation to the different stages of the design process, and research projects of a more limited extent, formulated on the basis of this review, are outlined. Finally, Chapter 8 summarises the projects and gives brief descriptions of these and the estimated staff requirement and financial commitment. The interrelationship between the projects is highlighted, and an outline strategic plan is presented for an integrated and nationally coordinated research effort.

thanks also to Gunilla Ljungquist who typed the manuscript, and to Lilian Johansson who drew the figures in the report.

Lund, May 1983

Robert Jönsson Ove Pettersson

1. DESIGN PRINCIPLES, PERFORMANCE REQUIREMENTS AND CRITERIA

1.1 Introductory review

Methods for the design of loadbearing structures under fire exposure conditions, which are applied internationally, may be described in outline with reference to the matrix set out in FIG. 1.1 /1.1/. This is based on three types of thermal exposure (H_1, H_2 and H_3) and three types of loadbearing structure (S_1, S_2 and S_3). The following typical definitions apply.

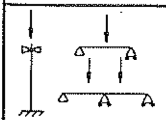
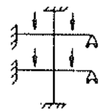
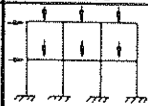
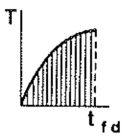
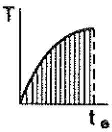
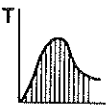
Model for structure / Model for thermal exposure		S_1 Element	S_2 Substructure	S_3 Complete structure
				
H_1	ISO-834  T, t_{fd}	test or calculation (deterministic)	calculation exceptionally testing (deterministic)	
H_2	ISO-834  T, t_e	test or calculation (probabilistic)	calculation, exceptionally testing (probabilistic)	calculation (probabilistic) should be avoided
H_3	real fire  T	calculation (probabilistic)	calculation (probabilistic)	calculation (probabilistic) in special cases and for research

FIG. 1.1. Schematic description of different methods for the design of loadbearing structures under fire exposure conditions.

S_1 - a simplification of a real loadbearing structure by breaking this down into individual elements such as beams and columns which are as a rule simply supported

S_3 - a real loadbearing structure.

H_1 - thermal exposure according to ISO 834 or national standards corresponding to this /1.2/. This exposure is predominant internationally in practical design and is based on the results of standardised fire tests and associated classification. In some countries it is permissible for such a classification to be alternatively based on the results of analytical calculations. The exposure is defined by the expression

$$T - T_o = 345 \log_{10} (8t + 1) \qquad (1.1)$$

where

t = time in minutes
T = furnace temperature at time t (°C)
T_o = furnace temperature at time t = 0 (°C)

The time t_{fd} specified for thermal exposure in a test or corresponding calculation varies according to the situation concerned, and is laid down in e.g. the Swedish Building Code (SBN).

H_2 - the same thermal exposure as that according to H_1, Equation (1.1). The time t_e of thermal exposure is determined in each individual case by the real fire process in the fire compartment. In practice, this is carried out on the basis of the equivalent fire duration t_e which is defined as the time required for thermal exposure according to ISO 834 which produces the same critical effect on the structure concerned as a real fire. For steelwork, the following approximate formula can be used /1.3/:

$$t_e = 0.067 \frac{f}{\left(\frac{A\sqrt{h}}{A_{tot}}\right)^{1/2}} \quad \text{(min)} \qquad (1.2)$$

where

f = fire load intensity in the fire compartment in MJ/m^2 of enclosing surface
A = total area of window and door openings, m^2
h = mean value of the height of openings, weighted with respect to the area of the opening concerned, m
A_{tot} = total internal enclosing surface of the fire compartment inclusive of openings, m^2.

H_3 - exposure due to a real fire. The exposure can be described in terms of a time curve relating either be determined on the basis of the heat and mass balance equations of the fire compartment, or from available manuals. FIG. 1.2 gives an example of such data, taken from the Commentary to the Swedish Building Code 1976:1.

To these typical definitions must be added the following comments regarding the models for thermal exposure, the H models.

Loadbearing and separating constructions of combustible material may themselves provide considerable additional input in the event of fire. This is not taken into consideration in furnace tests according to ISO 834, in which the input power of the furnace is regulated in such a way that the prescribed curve of the furnace temperature T as a function of time t conforms to Equation (1.1). In a given furnace, this requires an input power which is considerably less in a test on a structure of combustible material than in a test on a non-combustible material, particularly if the latter absorbs a large amount of the input power.

From the point of view of thermal exposure, the time curve for the heat flow rate supplied to the structure is critical with regard to the fire behaviour of a structure. International discussions are therefore taking place within ISO concerning a possible change to controlling thermal exposure in a furnace test so that it conforms to such a time curve for the rate of heat flow towards the element of construction being tested. However, it is at present difficult to predict whether such a change is probable.

In order to simplify description of the thermal exposure on a loadbearing and/or separating construction of non-combustible material in the event of fire, Harmathy has introduced the concept of normalized heat load which is defined by the expression /1.4, 1.5/

$$H_n = \frac{1}{\sqrt{(k\rho C)}} \int_0^{\tau} q \, dt \qquad (s^{1/2}\ {}^{o}C) \qquad (1.3)$$

where

q = the heat flow rate towards the constructions enclosing the fire compartment, at time t (W/m^2)
τ = duration of fire exposure (s)
$\sqrt{(k\rho C)}$ = the thermal inertia of the enclosing constructions ($J/m^2 s^{1/2}\,{}^{o}C$), where k = thermal conductivity, ρ = density, and C = specific heat capacity

This concept can be used to quantify the thermal exposure potential, both in conjunction with exposure accord-

The gas temperature-time curves for a real fire, which are exemplified in FIG. 1.2, presuppose a fire compartment of a size applicable to e.g. dwellings, ordinary offices, schools, hospitals, hotels and libraries. In the case of fire compartments of very large volume - e.g. industrial and sports premises - the curves do not give a good representation of the actual fire exposure. This is also true for the gas temperature-time curve (H_1) which is applied in standard fire tests.

In the event of a fire in large premises, a loadbearing structure may be subject to local exposure which is more intense than that described by the gas temperature-time curve according to FIG. 1.2. This may occur mainly in the case of loadbearing structures or elements which are placed in a corner of the premises or which, owing to their great height, form "screens" with intermediate spaces. It is known from real fires - e.g. from the fire at the Star Dust Club discotheque in Dublin on 14 February 1981 - that loadbearing and separating structures may in such an event be subjected to very high levels of exposure, up to 250 kW/m^2.

At present there is no analytical simulation model available which describes in a satisfactory manner the fire process in a fire compartment of large volume. Research in this area is therefore of high priority. This is also emphasised, for instance, in the fire research programme for the period 1982-84, adopted by the Swedish Board for Fire Research (BRANDFORSK), which contains a project B.17 "Fire spread and fire process in large premises", the primary object of which is to collate and evaluate the present state of knowledge in the field of fire physics, identify the need for research, and propose suitable projects. From the point of view of fire physics, work on such a programme consists of two parts. The first relates to the propagation and growth process of the fire, and is mainly based on a combustion technology approach. The second is based on a more refined fluid mechanics approach, and comprises determination of mass flows, temperature and velocity profiles in fire plumes, and gas flows below the ceiling.

In the light of these comments concerning the thermal exposure models, this introductory review is finally summarised by way of some views on the practical relevance of different combinations of H and S models.

As mentioned in the foregoing, the internationally dominant design procedure is based on thermal exposure according to Type H_1. The fire resistance t_{fr} of the loadbearing structure is normally determined by furnace tests according to ISO 834, but analytical calculation of t_{fr} is beginning to be accepted in an increasing number of countries as an alternative. See /1.6/ - /1.11/. The ISO standard has limited application for elements of construction such as beams, columns, walls, floors

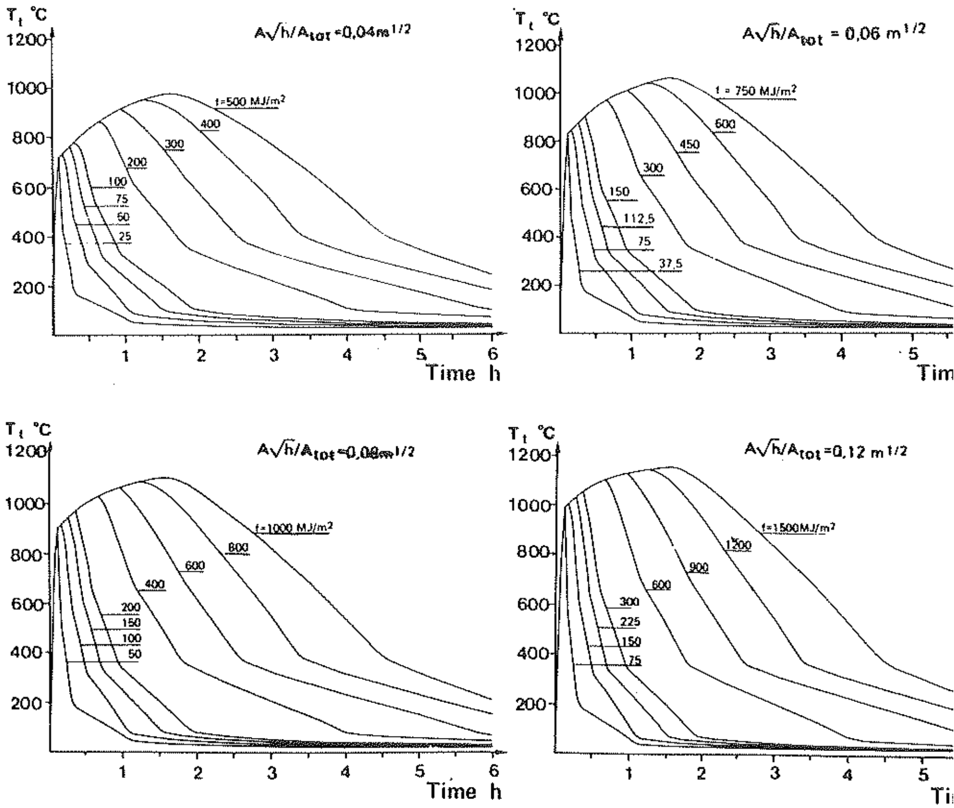


FIG. 1.2. Examples of gas temperature-time curves for a real fire as a function of the fire load intensity f and the opening factor $A\sqrt{h}/A_{tot}$ of the fire compartment. According to Commentary to the Swedish Building Code 1976:1, Fire Compartment Type A.

In a few countries, however, application of the procedure has been extended to the combination H_1 - S_2, primarily in association with analytical determination of the fire resistance. The combination H_1 - S_3 involves far too large an imbalance in the description of thermal exposure and loadbearing systems to be acceptable in practice.

A design based on natural fire exposure - exposure Type H_3 - is generally characterised by analytical treatment. For rapid practical application, it is necessary for systematised design data in the form of e.g. manuals to be available. In such cases it is usually the combination H_3 - S_2 which is used, and in certain cases the combination H_3 - S_1. Design according to the combination H_3 - S_3 generally demands access to a computer to be

Design for thermal exposure of the H_2 type is based indirectly on a real fire, described by the temperature-time curve according to ISO 834, Equation (1.1), with reference to the concept of equivalent fire duration t_e. The behaviour of a loadbearing structure, calculated for such an exposure, is different from its behaviour in a real fire situation in cases where the heating history is of significance. In the combination H_2 - S_1 design can be performed either analytically or on the basis of a furnace test according to ISO 834. In the combination H_2 - S_2 analytical design is the normal procedure, and experimental verification is an exception. The combination H_2 - S_3 is really a roundabout way of approaching a design according to the combination H_3 - S_3, and should therefore be avoided.

1.2 Internationally accepted conventional design

The internationally accepted conventional design method of fire design for loadbearing and separating structures may be summed up by the flow chart in FIG. 1.3.

The fire resistance t_{fr} of the element of construction is determined by the standardised Nordic test method NORDTEST FIRE 005 which is identical to ISO 834. The element of construction is subjected in a furnace test to thermal exposure according to Equation (1.1) - Type H_1 - within prescribed tolerances. Heating continues until the element of construction ceases to comply with the specified performance requirements, and the time at which this occurs defines the fire resistance t_{fr} of the element of construction.

For a loadbearing element of construction, the performance requirement implies that it shall not collapse at a time $t \leq t_{fr}$ for the actual load, selected according to Subclause 21:234 of the Swedish Building Code SBN 1980. For a separating construction the performance requirement implies that it shall be capable of preventing the spread of fire to the adjoining fire compartment for a time $t \leq t_{fr}$. As far as the test procedure is concerned, the performance requirement contains a sub-requirement concerning resistance to the penetration of flames and hot gases (the integrity requirement), and a sub-requirement concerning limitation of temperature rise on the face of the element of construction remote from the fire (the insulation requirement).

For an element of construction which has a dual loadbearing and separating function, all three performance requirements - the loadbearing, integrity and insulation requirements - must be complied with for $t \leq t_{fr}$. During design, according to FIG. 1.3, the fire resistance t_{fr} of the element of construction is to be related

$$t_{fr} \geq t_{fd} \quad (1.4)$$

For loadbearing elements of construction, the prescribed fire resistance classes are set out in Clause 37:32 of SBN 1980. These requirements are differentiated with respect to

- o the type of building
- o the magnitude of fire load
- o the number of storeys and the vertical position of the element of construction in the building
- o the consequence of the failure of the element of construction.

Similarly, for elements of construction with a separating function, the prescribed fire resistance classes are set out in Subclause 37:422 of SBN 1980.

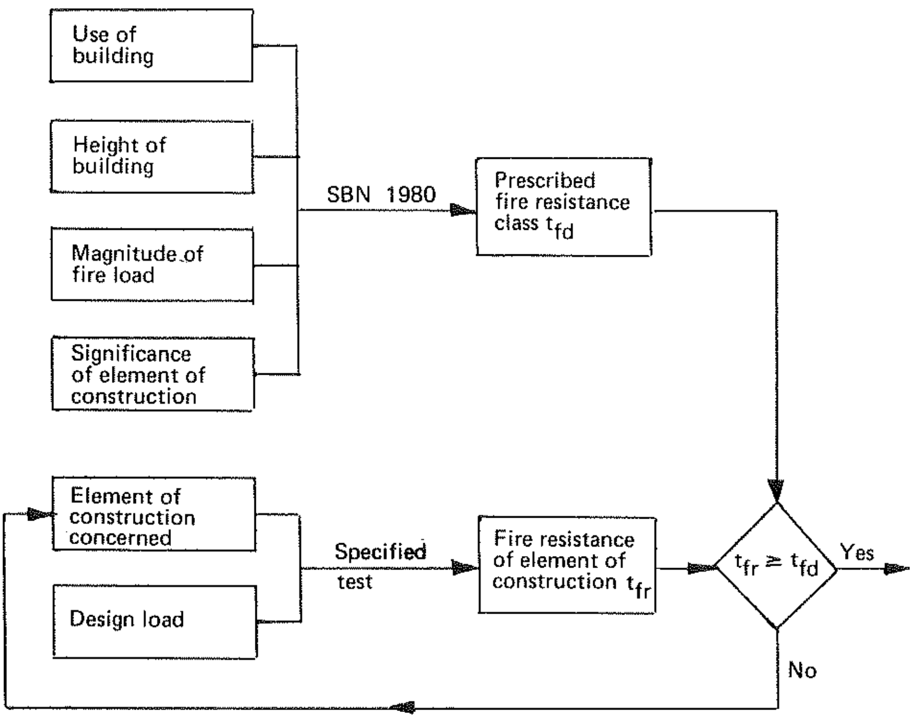


FIG. 1.3. Internationally accepted conventional design

1.3 Analytical design based on real fire exposure

In the last few decades, great advances have been made in the field of analytical fire design of loadbearing structures. The aim is to devise a design procedure which is based on the properties of the real fire process - exposure Type H_3 - the structure of which agrees with the design technique normally applied for the mode of action and loadbearing capacity of structures at ordinary temperatures.

FIG. 1.4 gives an outline of the calculation procedure. During design the least loadbearing capacity R_d of the structure during a fire is calculated, and this is compared with the design load effect S_d during the fire.

The design thermal exposure to which a loadbearing structure is subjected in the event of fire in a fire compartment is determined partly by the design fire load intensity f and partly by the properties of the fire compartment. The critical influence exerted by the fire compartment is due partly to the opening factor which is a function of the height and area of window and door openings, and partly to the thermal properties of the constructions enclosing the fire compartment, i.e. the type of fire compartment. See FIG. 1.2.

For a loadbearing structure whose properties are specified, the design fire exposure, together with data concerning the thermal properties of the material contained in the loadbearing structure and the surface heat transfer conditions relating to the free surfaces of the loadbearing structure, provides the basis required for determination of the temperature field of the loadbearing structure as a function of time. When the mechanical properties of the loadbearing material at elevated temperatures are known, this temperature field can be converted by calculation into the stress-strain curve at varying temperature and load levels of the loadbearing structure when this is exposed to fire. If this is then related to a failure criterion, the variation in time of the loadbearing capacity of the structure can be calculated.

The least value of this during the fire defines the design loadbearing capacity R_d which is to be compared with the design load effect S_d in the event of fire. The design requirement is that

$$R_d \geq S_d \qquad (1.5)$$

In general, SBN 1980 permits analytical fire design of loadbearing structures according to the procedure set out in FIG. 1.4 as an alternative to the conventional international design according to Section 1.2. The de-associated regulations for fire load intensity, loads and loadbearing capacity are given in Subclauses 21:234 and 37:332 b of SBN.

Practical application of the design method is made easier by manuals granted type approval by the Swedish Board of Physical Planning and Building /1.12/, /1.13/.

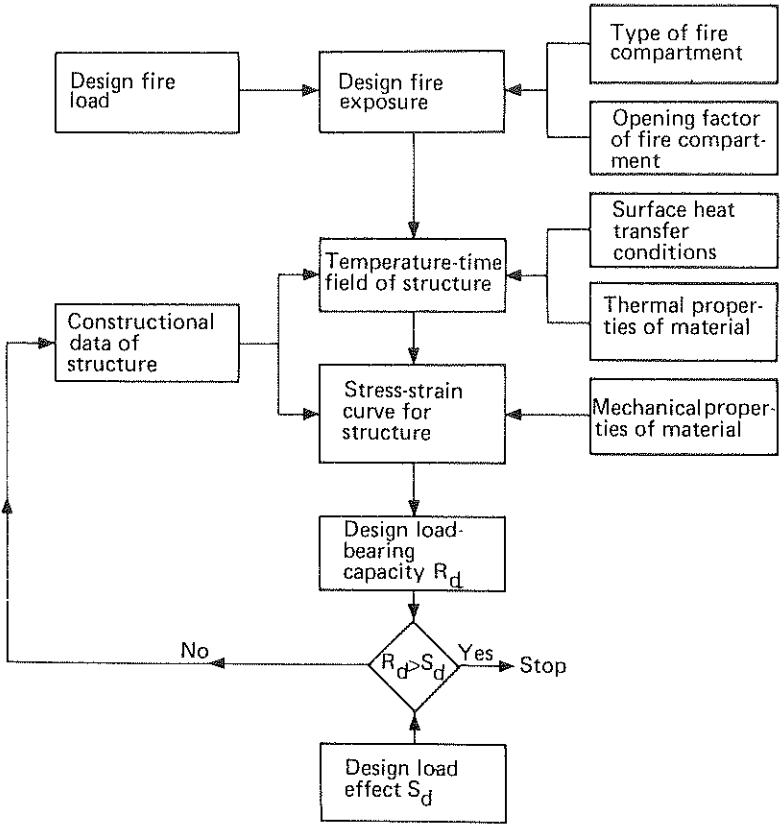


FIG. 1.4. Flow chart for analytical fire design of loadbearing structures on the basis of real fire exposure.

1.4 Design based on the concept of equivalent fire duration

As described in detail in Section 1.3, the Swedish Building Code permits analytical design of loadbearing and which is based on the results of fire tests according to ISO 834. In the as yet rare cases where similar analytical design is accepted in other countries, this is as a rule associated with the concept of equivalent fire duration - thermal exposure Type H_2. The equivalence is defined with reference to the criterion that the real fire and a thermal exposure according to ISO 834, Equation (1.1), shall produce the same critical effect with respect to the relevant limit state in the structure concerned.

For design based on the concept of equivalent fire duration t_e, the general requirement is that

$$t_{fr} \geq t_e \qquad (1.6)$$

where t_{fr} is the fire resistance of the element of construction, determined in a fire test according to ISO 834 or by corresponding calculation.

This requirement holds for both loadbearing and separating elements of construction.

In an accurate treatment, the equivalent fire duration t_e depends both on the parameters of the fire and on the constructional details of the element of construction /1.3/. For a more approximate treatment, formulae of the type exemplified by Equation (1.2), which are independent of the constructional details of the loadbearing structure, can be used. Approximate formulae of this type which are available have been verified as reasonable for loadbearing structures of steel and for reinforced concrete beams in which flexural failure is initiated by yield of the reinforcement. For other types of loadbearing structure and for elements of construction with a separating function, the concept of equivalent fire duration is as yet incomplete or has not been studied at all.

1.5 Fire design of loadbearing structures according to probabilistic methods

For some years, work has been carried out on existing design methods for loadbearing structures exposed to fire so that they may be adapted to modern safety theory methods of the type which has begun to be applied for the design of loadbearing structures in ordinary temperature conditions /1.14/ - /1.20/.

In order that such a development may be meaningful, the design method must be made up of functionally well de-procedure based on the results of fire tests according to ISO 834 or on corresponding calculation results - the H_1 method - does not meet this fundamental requirement. On the other hand, the methods described in Sections 1.3 and 1.4, which are directly or indirectly based on the characteristics of real fires - the H_3 and H_2 methods - lend themselves to further development in this respect.

For methods which are to be used in normal practical application, the natural aspiration level is thus to aim for the development of probabilistic methods in which the statistical influences are taken into consideration by means of characteristic values and partial safety coefficients specified for the quantities involved - loads, fire load, geometrical quantities, thermal properties, strength properties. For the derivation of the values of the partial safety factors, a probabilistic analysis based on some first order reliability method (FORM) is needed.

In such an analysis, the design criterion is that in the event of fire exposure a specified least safety margin shall be maintained with respect to the least loadbearing capacity of a loadbearing structure, and with respect to the highest temperature on the side of a separating construction remote from the fire. Expressed in terms of a safety index - defined as the ratio of the mean value of the safety margin to its standard deviation - the design criterion has the form

$$\beta_{fm} - \beta_r \geq 0 \qquad (1.7)$$

where β_{fm} is the least value of the safety index during the fire sequence involved, and β_r the specified value of the safety index.

Exemplified for a loadbearing structure of timber which is exposed to fire and which is designed according to the H_3 method (FIG. 1.4), a safety index analysis can be described in outline by FIG. 1.5.

On the basis of the magnitude and properties of the fire load and the geometry, ventilation and thermal characteristics of the fire compartment, the fire exposure is determined - described, for instance, in terms of the combustion gas temperature-time curve. In the next step, the reduced cross section of the loadbearing structure and the associated transient temperature and moisture conditions are calculated for this fire exposure on the basis of data relating to the configuration of the loadbearing structure and the thermal, moisture mechanics and combustion properties of the material of the loadbearing structure as input quantities. Using the strength and deformation properties of the loadbearing material e.g. the bending moment $M_R(t)$ at a critical section of the loadbearing structure.

The load which is statistically representative of the fire situation produces a maximum load effect with an associated bending moment $M_S(t)$ at the section where $M_R(t)$ is applied. This permits definition of the safety margin

$$Z(t) = M_R(t) - M_S(t) \qquad (1.8)$$

the risk of failure

$$P(t) = \int_{-\infty}^{0} f_Z \{Z(t)\}\, dZ \qquad (1.9)$$

and the safety index

$$\beta_f(t) = \phi^{-1}\{1 - P(t)\} \qquad (1.10)$$

where

$f_Z \{Z(t)\}$ = the distribution function for the safety margin $Z(t)$
ϕ^{-1} = the inverse of the standardised normal distribution.

In determining $Z(t)$, $P(t)$ and $\beta_f(t)$, the following factors must be taken into consideration:

- o the uncertainty in specifying the fire load
- o the uncertainty in describing the ventilation properties of the fire compartment and the thermal characteristics of the constructions enclosing the fire compartment
- o the uncertainty in the analytical model for determination of the fire process and its thermal effect on the structure
- o the uncertainty in specifying the geometry and imperfections of the structure
- o the uncertainty in specifying the thermal, moisture mechanics, combustion and mechanical properties of the structural material at elevated temperatures
- o the uncertainty in the analytical models for determination of the transient temperature and moisture states and the loadbearing capacity of the structure
- o the uncertainty in specifying the load

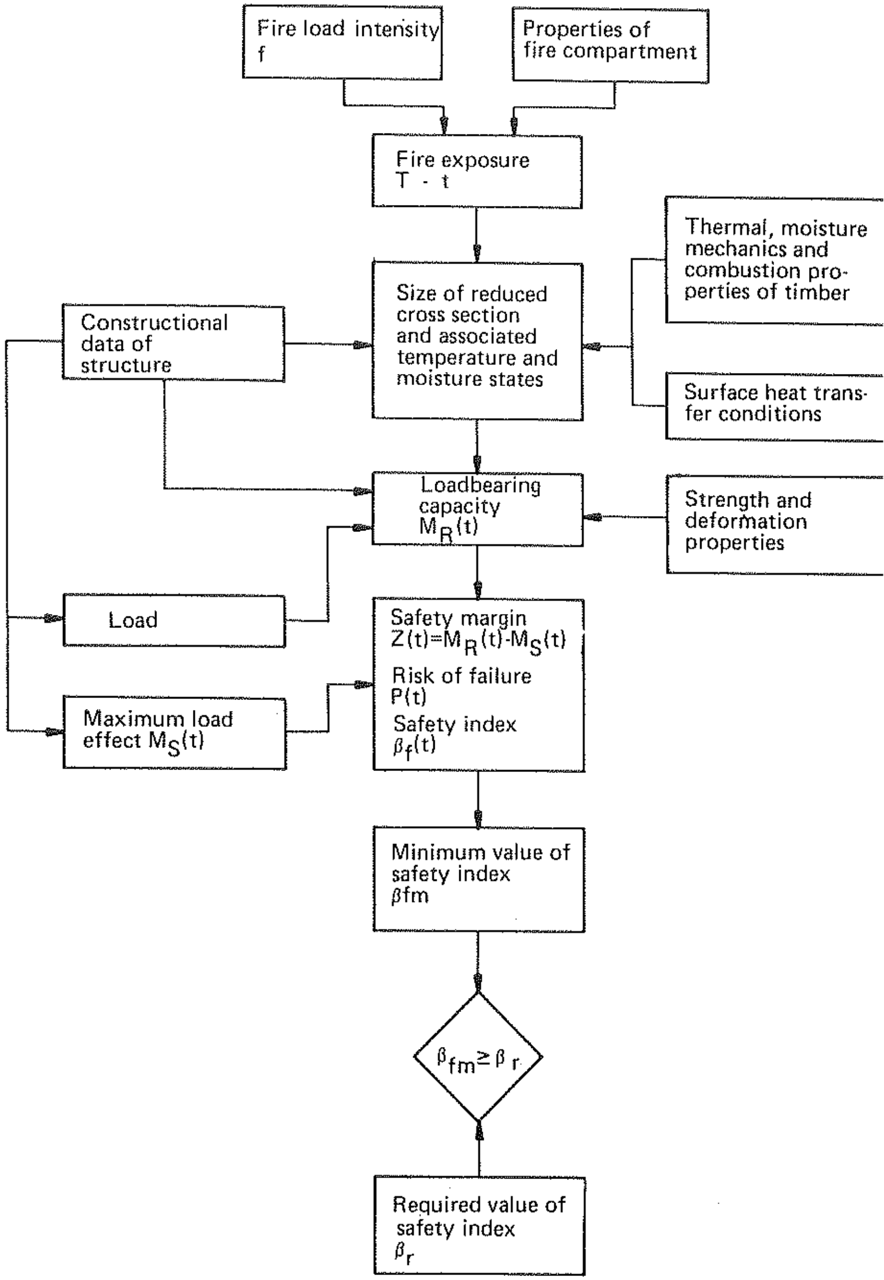


FIG. 1.5. Derivation of partial safety factors for a timber structure under fire exposure conditions on the basis of a safety index analysis.

The required value of the safety index β_r depends on the consequences of failure in the structure, the probability of occurrence of a fully developed fire, the attendance time of the fire brigade, and the effect of an automatic fire extinguishing system.

For design according to one of the H_2 methods, a procedure based on partial safety factors may be summarised in terms of the design criterion

$$\frac{t_f}{\gamma_f} \geq \gamma_n \gamma_e t_e \qquad (1.11)$$

where t_f is the fire resistance of the loadbearing or separating construction, determined experimentally in accordance with ISO 834 or by a corresponding calculation, and t_e is the equivalent fire duration determined, for instance, from Equation (1.2). γ_f, γ_n and γ_e are partial safety factors which together allow for all the uncertainties inherent in the design process.

The partial safety factor γ_e obviously refers to the uncertainties due to specification of the characteristics of the fire load and fire compartment, and to the uncertainties in the analytical model for the determination of the associated fire exposure. The partial safety factor γ_f allows for uncertainties in specifying the load and the thermal, moisture mechanics, combustion and mechanical properties of the structural material, and the uncertainties in the analytical models which determine the load effect, the transient temperature and moisture processes, and the loadbearing capacity of the structure. The partial safety factor γ_n takes into consideration the consequences of failure and the probability of occurrence of a fully developed fire, and the effect on this of the attendance time of the fire brigade and, if installed, an automatic fire extinguishing system.

1.6 Urgent research projects within the overriding area relating to loadbearing and separating constructions in the event of fire

It will be evident from the above

- o that fire classification of elements of construction based on analytical treatment instead of the results of furnace tests according to ISO 834 - FIG. 1.3 - is gradually being permitted in an increasing number of countries,
- o that, in Sweden, analytical fire design of load-

minant design procedure based on standardised thermal exposure according to ISO 834, FIG. 1.4, with the fire exposure exemplified by FIG. 1.2. This method is now beginning to gain a foothold in other Nordic countries, and is part of the instruction at a number of foreign universities,

- that international development is in progress to adapt these analytical design methods, based on a real fire sequence, to modern safety philosophy - FIG. 1.4 and 1.5 in combination,

- that development in Sweden in this respect is related to a direct design procedure according to the flow chart in FIG. 1.4, while in some non-Nordic countries development is taking place in association with an indirect design method in which a real fire sequence and thermal exposure according to ISO 834 are coupled by means of the concept of equivalent fire duration.

Analytical determination of the behaviour and loadbearing capacity in the event of fire of loadbearing elements of construction is today a practical possibility - as a rule with relatively little labour - for most types of steel structure. For loadbearing structures of reinforced and prestressed concrete the present design data are obviously inadequate. However, at the Division of Building Fire Safety and Technology, Lund Institute of Technology, design and development work has been taking place for some years on the production of a manual for analytical design of fire-exposed concrete structures, and it is expected that this will be ready in 1983. The manual gives systematic data both for determination of the fire resistance of elements of construction in conjunction with thermal exposure according to ISO 834, and for analytical design of a loadbearing structure on the basis of a real fire, adapted to modern loading and safety regulations /1.21/. For similar adaptation of the manual for fire design of steel structures, published in 1976 /1.12/, the Swedish Institute of Steel Construction has been allocated funds by BRANDFORSK. With regard to design calculations for loadbearing and separating structures in large premises, reference is to be made to the comments given in Section 1.1.

With regard to the concept of equivalent fire duration, the present state of knowledge verifies practical application of this only for steel structures and reinforced concrete beams subject to certain modes of failure.

For timber structures exposed to fire, fire resistance and loadbearing capacity can at present be calculated approximately for beams and columns of solid cross section. For lightweight and composite timber structures, even this is impossible. Probabilistic fire design and the concept of equivalent fire duration are research areas which are at present practically untouched as

It is of urgent necessity that knowledge concerning the behaviour and design of timber structures under fire exposure conditions should be developed to a level similar to that for steel and concrete structures. This is essential in order that steel, concrete and timber may in the future be able to compete on equal terms as materials for loadbearing and separating constructions.

With regard to types of problem, development towards such a balanced state of knowledge may be broken down into the following overriding research projects:

(1) Development of methods for analytical determination of the fire resistance of elements of construction of timber in conjunction with thermal exposure according to ISO 834.

(2) Development of methods for fire design of loadbearing and separating timber constructions on the basis of a real fire.

(3) Production of data for determination of the equivalent fire duration for elements of construction of timber.

(4) Further development of the design method according to (2) with a view to adapting this to modern loading and safety regulations based on probabilistic methods.

Projects (1) and (2) comprise broadly related research projects and should therefore be treated in parallel. Project (3) is based on the results of Projects (1) and (2). Project (4) necessitates as its basis a design method made up of functionally well defined and verified analytical models of the type applicable to Project (3).

On the basis of an international assessment, all four research projects are of great urgency. Nationally, Project (3) has a lower degree of priority than the others as a result of the fire design philosophy decided on in the Swedish Building Code.

The overriding research projects (1), (2) and (3) each contain a number of subprojects with well defined areas. In the order in which they are encountered in a design process according to FIG. 1.4, these are

- Development of an analytical model for calculation of the rate of charring under variable thermal exposure, and production of material data for such a model,
- development of an analytical model for calculation of transient temperature and moisture states for uncharred portions of the cross section, and production of material data with respect to heat and moisture transfer for such a model,

- analysis of the physical and chemical mechanisms involved in the action of flame retardants, and determination of the possibilities of optimum interaction between different mechanisms,
- development of an analytical model for calculation of the behaviour and loadbearing capacity under fire exposure conditions of solid, lightweight and composite timber structures with the above models for rate of charring, heat and moisture transfer and the mechanical behaviour of timber as the components,
- development of analytical models for the thermal and mechanical behaviour of joints and connections under fire exposure conditions.

Most of these projects can be dealt with as independent research tasks. If this is done, it is essential that the individual tasks should be planned in view of the fact that, in practical application, they are to be integrated components of a total design process. All projects include experimental verification at model or full scale as an essential and obvious element. It is important in this connection that the possibility of making use of published experimental results for such verification should be fully examined.

The overriding design project No (4) contains, as part of a process of deriving partial safety factors for timber structures, an analysis of

- the uncertainties in the analytical models for calculation of the rate of charring, heat and moisture transfer, and mechanical behaviour and loadbearing capacity,
- the uncertainty in specifying the combustion, thermal, moisture mechanics and structure mechanics material properties,
- the mutual significance of the uncertainties in the various design components, with a view to ascertaining the parts of the design process on which research should concentrate.

The research tasks comprised in these overriding research projects are described in greater detail in the following chapters.

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2. IGNITION

2.1 Introduction

Prediction of whether or not ignition will occur due to different external thermal exposures is a very complex problem. A large number of factors influence the processes leading up to ignition, and it is impossible to devise unambiguous ignition criteria which are valid in all cases. In addition, the definition of ignition varies between different investigations, and this makes comparison of experimental data difficult. NBS defines the ignition temperature as the lowest temperature from which, under favourable conditions, a material spontaneously heats up until glowing or flaming occurs. According to Graff /2.1/, ignition is defined as "when the rate of heating in the substrate exceeds the rate of external heating and has visible flaming or glowing as a result". There are also other definitions.

The most important aim of studies of the ignition process is to develop verified theories and methods which permit determination of whether ignition will take place as a result of a specific exposure, and whether, after ignition, the material will continue to burn (sustained flaming). Experiments which have been carried out had the object of ascertaining the time to ignition for materials subject to external thermal exposure. The influence of various factors on ignition time was studied, and an endeavour was also made to determine a specific ignition temperature. Ignition theories have been presented, but owing to the high degree of complexity of the problem these have produced complicated results with many factors of uncertainty. The foremost reason for this is that wood under thermal exposure constantly changes. The theories have been found most useful for the study of flame spread expressed in terms of a series of successive ignitions. The ignition temperatures established for wood based materials are mainly useful for purposes of classification. On the other hand, they cannot be used for precise prediction of the behaviour of a material in a real fire situation.

2.2 Different types of ignition

In determining ignition criteria, a distinction can be made between two types of ignition, one with and one without a pilot. In the pilot case, a small flame is placed immediately in front and above the material under test. Ignition occurs when a flammable gaseous mixture of decomposition products and air reaches the flame. The flame may also be in direct contact with the surface, a developed fire. Ignition without a pilot is designated spontaneous ignition, and occurs when the gaseous mixture itself has attained a high enough temperature to ignite. Spontaneous ignition can be further broken down into two cases depending on the time of exposure. These different types of ignition are set out in FIG. 2.1. Spontaneous ignition is of the greatest importance for the study of flame spread between separated objects. Ignition both with and without a pilot occurs in a similar manner.

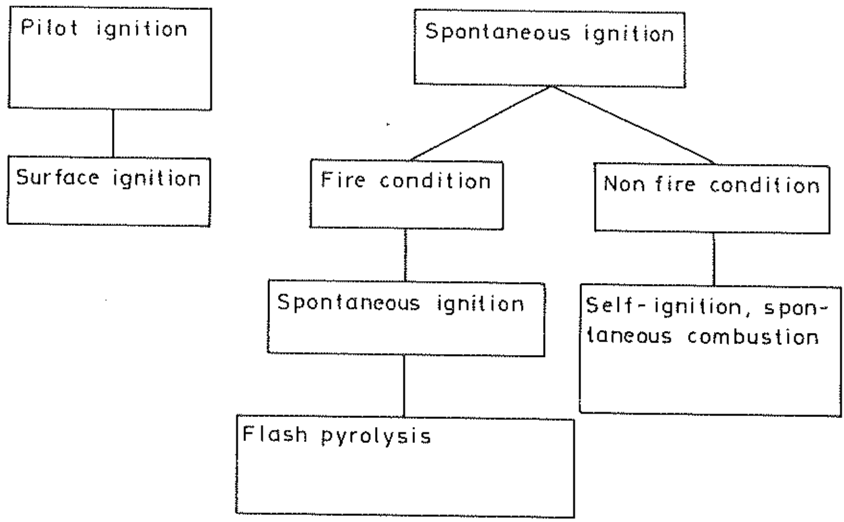

FIG. 2.1. Different types of ignition.

2.3 Factors which influence ignition

FIG. 2.2 illustrates schematically the different events during the ignition process for a solid body exposed to external heat radiation on one side. That part of the radiation which is absorbed heats the wood next to the surface. This heating causes thermal breakdown of the wood and the emission of flammable gases. The quantity of energy absorbed depends on the level of radiation and on the transparency of the wood to radiation, i.e. on the diathermancy of the wood. Transparency is determined by the spectral distribution of radiation, the reflectance of the surface and the wavelength dependent absorption of the wood. If the effective absorption coefficient is large, most of the external radiant energy will be absorbed in a thin layer at the surface. The temperature in such a case rapidly increases to levels reradiation level required for ignition are therefore governed by the properties of the wood and the spectral distribution of radiation.

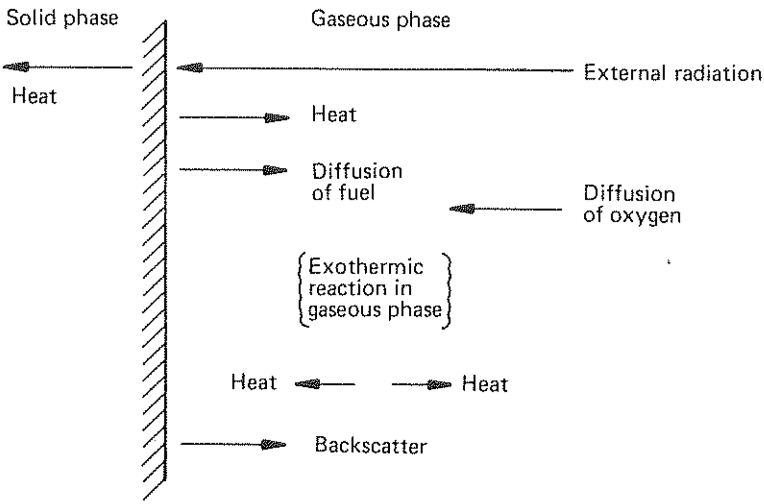

FIG. 2.2. Ignition scenario for solid fuel subject to external heat radiation /2.2/

When the wood breaks down, gases are emitted from the surface, and by diffusion and convection these are mixed with the oxygen in the air. Exothermic reactions are set up. Simultaneously, the gases next to the surface are heated up by convection from the hot wood surface and by absorption of the external radiant energy.

The gases can reach a temperature higher than the surface temperature. As these processes are taking place, the number of exothermic reactions and thus chemical production of heat increases. This causes further thermal decomposition of the wood and increased emission of gases, which in turn accelerates the rate of reaction, and finally these processes result in ignition.

The parameters normally studied in ignition tests are the ignition time, surface temperature, temperature distribution in the material, loss of weight, absorption of radiant energy, moisture ratio, and convective effects. These parameters are governed both by material properties and the test and measurement technique selected. The essential factors which govern ignition are

(1) the heat source

(3) surface structure and absorption

(4) size of test specimen

(5) the ignition flame

(6) density and thermal properties of the material

(7) initial moisture ratio of the material

(8) thermal decomposition of the material.

Comments will now be made regarding these factors.

(1) The most important form of heat transfer in a fully developed fire is radiation, and for this reason radiation has been the most common heat source in ignition tests. Ignition owing to convective heat and conduction of heat from hot plates has also been studied /2.3/. The latter is of interest in conjunction with the study of splices and connections. The influence of convective heating is also significant for the ignition of e.g. wood in roof structures.

Examples of radiant panels which have been used are gas fired radiators, electric radiant panels, arc discharge lamps, tungsten filament lamps, and flames from liquid fuel burners. A gas fired radiator has a surface temperature of about 1000 K and a radiation level < 50 kW/m^2. Arc discharge lamps have been used to simulate radiation from nuclear explosions, and have a radiation level < 4200 kW/m^2. For exposure of larger test specimens, tungsten filament lamps which have a surface temperature of about 2500 K are used. (A comparison of these radiant panels is given in Simms /2.4, 2.5/). Flames from liquid fuel burners have been used for radiation levels < 130 kW/m^2 /2.6/.

At the same radiation level, the different radiant panels give rise to different ignition times. This is partly explained by the fact that spectral distribution of the emitted energy is different, and the material which receives the radiation absorbs different quantities of energy. Furthermore, certain types of radiant panel cause disturbances in flow conditions at the material surface. Another important factor is that backscatter from the material towards the radiant panel and the surroundings varies between different test arrangements.

(2) One of the conditions necessary for ignition to occur is that the flammable gases which leave the material must become mixed with the air, so that an ignitable gas may be formed. This can take place either through turbulent mixing or through diffusion under laminar conditions. Ignition then occurs when the gas mixture has the correct concentration and temperature. Ignition may occur either with the aid of a flame (pilot ignition) or within the gas mix-

height is necessary, and for radiation intensities less than a certain value the ignition time depends on the height of the specimen up to a critical height. For specimens of greater height the ignition time is influenced by free convection. (These conditions are described in Alvares et al /2.7/). At low intensities, a moderate artificial draught produces a reduction in ignition time. This does not hold for higher radiation intensities. There are also indications that a strong draught increases the ignition temperature irrespective of radiation intensity /2.1/. Furthermore, ignition time decreases if the concentration of oxygen increases. As a certain least radiation intensity is always required in order that ignition may occur, this minimum level may be affected by the presence of a draught /2.3/.

(3) In Strömdahl /2.8/ there is a description of an experimental investigation which contains a study of the effect of different types of surface treatment. An example of the results is given in FIG. 2.3. The investigation shows, inter alia, that wrought timber has a lower ignition time than sawn timber, and that a higher resin content tends to reduce ignition time.

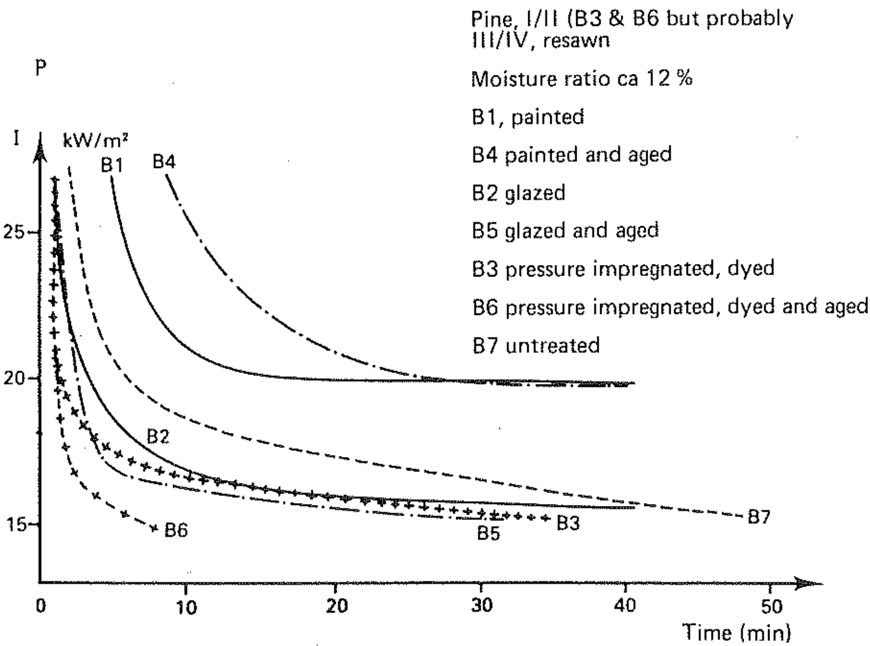

FIG. 2.3. Relationship between ignition time t_{ig} and the level of constant radiation intensity P

Wood is to some extent diathermic (transparent to thermal radiation), and a diathermic material ignites at a lower surface temperature than one which is not diathermic. This diathermic effect decreases and becomes negligible when thermal decomposition of the wood begins /2.5/. Investigations show that absorptivity (the ratio of the intensity required for ignition of a sooty surface to that required for ignition of a non-sooty surface for one and the same ignition time) increases with the time of exposure, and gradually reaches a constant value.

(4) Small surfaces (< 10 cm^2) require a higher least radiation intensity than larger surfaces in order to ignite /2.3/, and in most cases the small surface will glow while the larger one will produce a flame. The size of the surface also affects flow conditions, as described under (2) above. This state of affairs shows the difficulties involved in directly converting small scale results into full scale results. Some works indicate that for radiation intensities > 130 kW/m^2 the ignition time at small scale should be reduced by multiplication by a factor of 0.8 in order that good agreement with full scale conditions may be obtained. Radiation of such high levels is primarily of interest in connection with civil defence.

Wood is regarded as thermally "thick" - i.e. thermal exposure of one side of a panel produces negligible effect on the unexposed side - for thicknesses of 10-20 mm, depending on the level of radiation. For thicknesses greater than these values, ignition time is not affected by variations in thickness. For smaller thicknesses the ignition time decreases in direct proportion to the thickness /2.4, 2.9/.

(5) In order that the pilot flame configuration should not exert an influence on the ignition time, the pilot flame must be placed in such a way that it transmits a negligible amount of energy to the material. Its size shall further be such that it covers an uneven mixture of pyrolysis products and air. This means that the pilot flame should be placed immediately in front and above the upper front edge of the test specimen.

(6) For a short time at the commencement of thermal exposure, the diathermic properties of wood are important with regard to the quantity of energy transmitted to the wood. This effect then vanishes owing to thermal decomposition of the wood, and convection becomes the dominant transport term /2.10/. A higher density and a higher thermal conductivity increase the ignition time /2.11, 2.12/.

(7) The time to ignition and the minimum radiation inten-

pilot, moisture ratios less than 20% have little influence on ignition time, and for moisture ratios less than 40%, variations in moisture ratio have little effect on the required minimum radiation intensity. The influence of moisture is considerably greater in conjunction with spontaneous ignition. As the moisture content rises, the ignition time increases owing to the rise in thermal conductivity, transfer of heat due to diffusion of water, and vaporisation of water /2.12/.

(8) When wood is heated, a number of chemical reactions occur which break wood down into simpler components. Depending on the temperature distribution, different reactions take place, and this affects the type of pyrolysis product which leaves the surface of the material. It also influences the mixing ratio between air and flammable gases which is required for ignition. Wood is therefore classified into characteristic zones depending on the temperature. Detailed descriptions of these are given in Chapter 4.

2.4 Mathematical models

Existing mathematical models have been developed bearing in mind the requirement that they should be easy to apply. Because of this, the number of variables in these models is small. The variables included vary between authors, as a result of differences in opinion as to the factors which are of the greatest importance and those which can be ignored. Furthermore, the models have in most cases been developed in conjunction with an experimental series, and this also affects the number of variables.

Taken together, the various models should eventually result in a model which describes events from the time external thermal exposure begins until the time ignition occurs. Ideally, such a model should be capable of handling an arbitrarily selected heat source and should also take into consideration each change which occurs in the material up to ignition. Our imperfect knowledge at present with regard to identification of the reactions which take place in the material will probably make it very difficult to formulate such a "complete" model.

Research at present concentrates on studies of individual variables with the object of finding critical levels of these in a more perfect mathematical model.

In conjunction with studies of spontaneous ignition in fire conditions, knowledge of the heat balance in the material is essential. Unfortunately, a lot of this pletely evaluated. Simms /2.10/ mentions the following variables which should be included in studies of the heat balance for ignition of dry wood:

(1) The external heat source, usually radiation, which is absorbed in the surface layer if the material is opaque, or inside the material if this is diathermic,

(2) thermal conduction perpendicular to the surface,

(3) heat capacity,

(4) convective heat transfer in the material owing to gas transport,

(5) heating due to thermal decomposition,

(6) cooling of the surface.

The reason why treatment has been confined to dry wood is that further difficulties are encountered when moisture dependent effects are to be taken into consideration. This simplification is fully acceptable, since it is the most critical case which is studied /2.12/.

In solving the heat balance, Simms ignores the diathermic properties and the heat increment owing to the chemical reactions. Since a number of heat transfer variables are included and it is also difficult to decide which of these dominate, a large number of simplifications are made.

When a model of the heat balance has been constructed in this way, this shall be coupled to an ignition criterion. It is usual to choose a specific temperature, or a least emission of pyrolysis products, or a critical concentration of flammable gases and air /2.3/. There are further proposals regarding ignition criteria, and different formulae have also been proposed for determination of the time to ignition on the basis of a certain exposure. Lawson and Simms /2.13/ present a formula for qualitative assessment of the time to ignition.

Jentzsch /2.14/ is of the opinion that spontaneous ignition takes place if the following three conditions are simultaneously satisfied:

(1) A certain least temperature,

(2) sufficient production of pyrolysis products,

(3) sufficient concentration of oxygen at this temperature for the formation of a flammable gas mixture.

When a pilot is present, this replaces condition (1) above.

Ignition with a pilot differs from spontaneous ignition only as regards the ignition criteria. The pilot ignites the products of pyrolysis earlier, and otherwise has no influence. When the pilot is in contact with the surface

At different gas concentrations it has been found that a gas mixture temperature of 350°C is commensurate with ignition in the presence of a pilot /2.15, 2.16/.

In studies of ignition with a pilot, use can be made of a theory developed in order to describe extinguishment of liquid fires by cooling. This theory defines a critical surface temperature, the fire point, which is sufficient to ignite the material and to sustain a flame after the ignition source has been removed. This temperature is higher than the flame point of a liquid.

Previous work has shown that when liquid fires are extinguished with water by cooling these down to the fire point, this is the reverse of the process of ignition with a pilot /2.17/. Rasbash /2.18/ has developed this theory further so that it can also be used for solid materials, and it is therefore easier to study the conditions under which a material ignites. Apart from a critical surface temperature, the following three conditions must also be satisfied in order that ignition may take place:

(1) Sufficient convective heat transfer from the flame to the surface,

(2) sufficient production of pyrolysis products,

(3) sufficient flame temperature.

There are other ignition criteria.

Application of a critical least radiation intensity has little relevance in a fire situation in which surface ignition is in most cases dominant. Unfortunately, studies of ignition have concentrated on sponteneous ignition to the detriment of other forms of ignition.

2.5 Conclusions

A large number of experimental investigations have been reported in which most of the factors which influence ignition of wood have been studied. Comparative analysis of the available data is difficult, due, among other things,to the fact that different test techniques have been used in these investigations and different definitions of ignition have been applied.

Mathematical models have been developed from which the time to ignition can be calculated as a function of a temporally constant level of radiation. In real fire situations, exposure of a material to fire varies in time, and a pilot flame can reach the exposed surface at different times during a heating sequence. It is therefore difficult directly to predict the ignition time in actual fire conditions on the basis of calculation results yielded by these models. Duhamel's theopendent thermal conditions into time-dependent ones. Application of this in this context presupposes partly that ignition is governed by the surface temperature, and partly that all thermal data required for calculation are known.

In the light of this, development of simplified models which can translate a radiation-ignition time curve, determined either experimentally or analytically for constant levels of radiation, into an ignition criterion for a fire environment which is variable in time, appears to be a research project of great urgency. A proposal for such a model is presented in /2.19/.

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3. THERMAL PROPERTIES

3.1 Introduction

Accurate knowledge of the thermal properties of charred layers and of uncharred wood is necessary for calculation of the non-steady temperature field of timber structures under fire exposure conditions. Complications arise in this respect due to the anisotropy of wood, its biological variation within a structure, and the not insignificant variation of thermal properties with temperature and moisture ratio. This explains the present incomplete state of knowledge concerning the thermal properties of wood, in spite of a large number of reported investigations. These thermal properties are as follows:

Specific heat capacity	C_p (J/kgK)
Thermal conductivity	k (W/mK)
Enthalpy rise	ΔH (J/kg)
Phase transition energy	Q_L (J/kg)

3.2 Specific heat capacity

The specific heat capacity can be determined experimentally by the following methods:

Ordinary calorimeter

Bunsen ice calorimeter

Vacuum calorimeter

Heat flow methods

Differential scanning calorimetry (DSC).

Reference is to be made to the literature for more detailed descriptions of these methods. Only some of the data obtained by the various methods are given here.

For oven dry wood, the following values apply at temperature T°C:

Reference	C_p kJ/kgK	temperature range	method
Dunlap /3.1/	1.11 + 0.0049 T	0 - 112	Bunsen
Koch /3.2/	1.11 + 0.0042 T	60 - 140	DSC

and for wood of moisture ratio m%

Reference	C_p kJ/kgK	temperature range	method
Vohlbehr /3.3/	1.08 + 0.0041 m + 0.0025 T + 0.00006 mT	0 - 100	Bunsen

Measurement of heat capacity does not normally involve any major difficulty.

Few values exist for the specific heat capacity of carbon, and those that are available have considerable scatter.

Buller /3.4/ uses $C = 0.50$ kJ/kgK

Perry /3.5/ uses $C = 1.01$ kJ/kgK

For the flammable gases, Bullen /3.4/ uses C = 1.8 kJ/kgK.

3.3 Thermal conductivity

Thermal conductivity can be experimentally determined by the following methods:

Lee's disc method

Hot wire method

Differential scanning calorimetry (DSC).

McLean /3.6/ gives the following equation for wood of moisture ratio m % and density ρ kg/m³ radially to the grain:

$$k = (2.0 + 0.0406m)\,\rho \times 10^{-4} + 0.0238 \text{ W/mK} \quad m < 40\%$$

$$k = (2.0 + 0.0544m)\,\rho \times 10^{-4} + 0.0238 \text{ W/mK} \quad m \geq 40\%$$

Thermal conductivity is also temperature dependent, and Kollman /3.7/ has found that in the temperature range 0 - 100°C the thermal conductivity is approximately directly proportional to absolute temperature.

According to Griffiths and Kaye /3.8/, thermal conductivity in the tangential direction is 0.9 - 0.95 times that in the radial direction, and in the longitudinal direction it is 1.75 - 2.25 times that in the radial

For carbon, values of k between 0.076 and 0.94 W/mK have been reported, but no information is given as to what temperature and density they refer to. Hadvig /3.9/ found in his experiments that for carbon layers thicker than 6 mm, k = 0.38 W/mK is an acceptable value.

3.4 Enthalpy and energy of phase transition

Enthalpy is usually measured in a bomb calorimeter. Information concerning the enthalpy of wood is given in Harmathy /3.10/, Roberts /3.11/ and Thomas and Nilsson /3.12/, the value for dry wood being between 18 and 19 MJ/kg.

Thomas /3.13/ has developed a model for the calculation of the enthalpy of the gases when the enthalpies of wood and carbon are known together with the temperature, heat capacities and the proportion of wood which has been vaporised.

There is a coupling between the energy of phase transition, which varies between 0.4 and 0.5 MJ/kg, and the enthalpy, but this is complicated.

The following examples are taken from Böhm /3.14/ and refer to dry wood:

Energy of phase transition MJ/kg	5.4	2.7	1.35
Enthalpy of flammable gases	24.2	21.5	20.15

During a fire, the thermal properties and the proportion of wood which is pyrolysed per unit time both change, which makes calculation of the enthalpy of the flammable gases difficult.

3.5 Conclusions

Expansion of the present state of knowledge concerning the thermal properties of wood should focus primarily on the thermal conductivity and specific heat capacity of both charred and uncharred wood within the temperature range above 100°C. Priority should also be given to development of the relationship required for calculation of the heat of reaction of wood in real fire conditions on the basis of data regarding enthalpy and phase transition energy.

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4. RATE OF CHARRING, TEMPERATURE AND MOISTURE STATES

4.1 Introduction

In fire design of loadbearing and separating constructions of timber, knowledge of the non-steady temperature, moisture and density-time fields relating to the construction is essential information. From the density-time field, a reduced cross section at any elapsed time can be determined. This reduced cross section, the temperature and moisture-time fields and the associated changes in the mechanical properties of wood then form the basis for determination of the structural behaviour and loadbearing capacity of the construction under fire exposure conditions.

The behaviour of wood subject to thermal exposure is governed by a large number of physical and chemical mechanisms, the most important of which are

- o the internal convective heat flow due partly to gases and water which are formed during pyrolysis and which are transported both further into the wood and towards the exposed surface, and partly to transport of initial water,
- o thermal conduction and its modification by variable temperature and moisture content,
- o storage of heat,
- o exchange of heat at the material surface in the form of radiation and convection, inclusive of the effects of mass transport,
- o vaporisation of water, and
- o the chemical reactions which take place at varying temperatures and moisture contents in the wood.

The problem is complicated by biological variation of the wood.

Derivation of accurate mathematical models for determination of the rate of charring and the temperature and moisture gradients which fully allow for all these complex physical and chemical mechanisms, is a task of awesome complexity. In addition, the task is also meaningless in practice since there is no information available concerning most of the material parameters. Effort has so far been directed instead at the development of approximate one-dimensional models for initially dry wood. These models have been verified experimentally. Application of the models excludes thin-walled timber structures. The following may be mentioned among published models: Fredlund /4.1/, Roberts /4.2/, Kansa-Perlee-for calculation of the rate of charring in timber structures exposed to a real fire characterised by the curves in FIG. 1.2. The models reported in /4.1/ and /4.4/ include determination of the temperature field within the uncharred portion of the structure. Reference /4.1/ also outlines an approach for treatment of the transient moisture state.

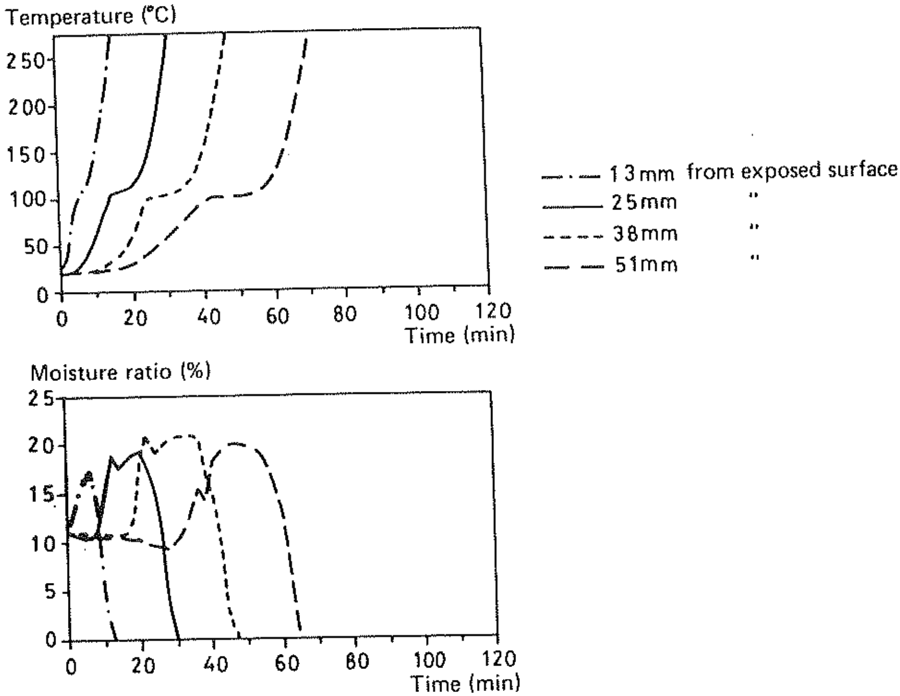


FIG. 4.1. Temperature-time and moisture ratio-time curves for redwood panel exposed to fire according to ISO 834 on one side /4.6/.

The most detailed experimental investigations have been reported by Hadvig /4.5/ and White-Schaffer /4.6/. The latter report presents accurate moisture gradient measurements which illustrate, inter alia, the steep rise in moisture which occurs at different points of the cross section of a timber structure exposed to fire, and which reaches its maximum at each point when the 100°C isotherm is passed. See FIG. 4.1.

4.2 Thermal decomposition

Wood is an organic material made of a number of components of individual chemical properties. Analytical simulation of the behaviour of wood by combining these components results in complex treatment which is made yet more difficult by "defects" in the form of variations in the biological structure of wood etc.

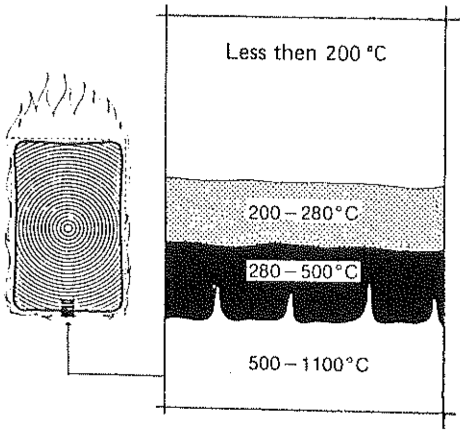


FIG. 4.2. Characteristic zones in wood during pyrolysis.

Studies of wood at elevated temperatures (pyrolysis) have given the result that, during pyrolysis of wood, four characteristic zones can be distinguished parallel to the heated surface. See FIG. 4.2. The following description is based on /4.7/.

Zone A. Temperature less than 200°C

The gases formed during a very slow pyrolysis are not ignitable. Wood is subject to a slow loss of weight. In certain cases, wood may begin to char above 95°C. There is oxidation of the charred layer which is exothermic and which, in circumstances when the heat is stored, can result in self ignition. However, sound wood - without e.g. decay - does not ignite in Zone A.

Zone B. 200° - 280°C

Even though the gases emitted are not ignitable, an exothermic state is reached during pyrolysis. The temperature at which the net result of all pyrolytic reactions until temperatures which are higher than those applicable to Zone B are reached.

Zone C, 280° - 500°C

The gas mixture which is emitted in large quantities in Zone C initially contains far too much carbon dioxide and water vapour to be ignitable. Gradually, however, flammability increases due to another and more rapid pyrolysis. At this stage combustion with a flame occurs only in the gas phase outside the wood, the reason being that there must be time for the rapidly emitted gases to become mixed with suitable proportions of atmospheric oxygen. Self sustaining diffusion flames from organic fuels burn at a temperature of about 1100°C. The charcoal formed cannot burn but is accumulated so long as production of gas is sufficiently large to isolate the surface of the wood from oxygen. As charcoal has lower thermal conductivity than wood, the layer of charcoal retards penetration of heat and the occurrence of an exothermic state in parts of the wood further inside.

Zone D, above 500°C

At 500°C charcoal glows and is oxidised. When the surface temperature attains a value just over 1100°C, charcoal is consumed at the surface just as fast as the penetration of the reactive zones.

When the reactive zones have penetrated so long that all original wood has been burned, the luminous diffusion flames cease, and only the non-luminous flames of burning carbon monoxide and hydrogen remain.

If we wish to mark approximately the boundary between charcoal and wood which has more or less escaped mechanical destruction, some investigations indicate that a temperature of 300°C is a usable criterion.

4.3 Charring processes

Two distinct processes govern the rate of charring, namely reaction kinetic processes and transport processes. The kinetic processes describe the rate at which chemical reactions occur at a certain temperature, and the transport processes the way and the time at which this temperature is reached. Which of these dominates is governed by the thickness of the material. It is a satisfactory rule of thumb that a thin material is governed by the

When solution is carried out with reference to a pyrolysis model, extensive simplifications are made at present by analysing pyrolytic data with the aid of a first order Arrhenius function which can be written

$$\frac{d\rho}{dt} = -\rho b e^{-(E_A/RT)} \qquad (4.1)$$

where

ρ = density of the material at time t
R = universal gas constant
T = temperature in K
b, E_A = constants where E_A denotes the activation energy

These two constants are obtained by thermogravimetric measurements on small test specimens or by measurements of density and temperature at different points on small or large test specimens. Determination of these constant presents great difficulties, since the constants must reflect all pyrolytic reactions, each of which has a separate process at different temperatures. The variable biological, chemical and physical structure of the wood sample also exerts an influence.

Another difficulty is presented by measurement of the heat of reaction, which for wood varies within wide limits depending on the conditions which obtain during pyrolysis. The heat of reaction can be determined by differential calorimetric measurements on small specimens or by means of energy balance calculations in combination with tests on large specimens.

In determining the constants b and E_A and the heat of reaction, correction for moisture has so far been made only for the heat of reaction.

A more detailed description of the combustion mechanisms of wood is given in Fredlund /4.1/.

The transport processes contain the following components

- conduction of heat
- diffusion of oxygen through wood and carbon
- transfer of gas inclusive of water vapour through wood and carbon.

The rate of combustion of wood is probably mainly govern by four parameters, namely density, permeability along t grain, moisture ratio, and thickness. Thermal conductivi is also important, but this is largely determined by density. In experiments on different wood species, thicknesses, moisture ratios and radiation intensities, it has been found that the loss of weight is proportional

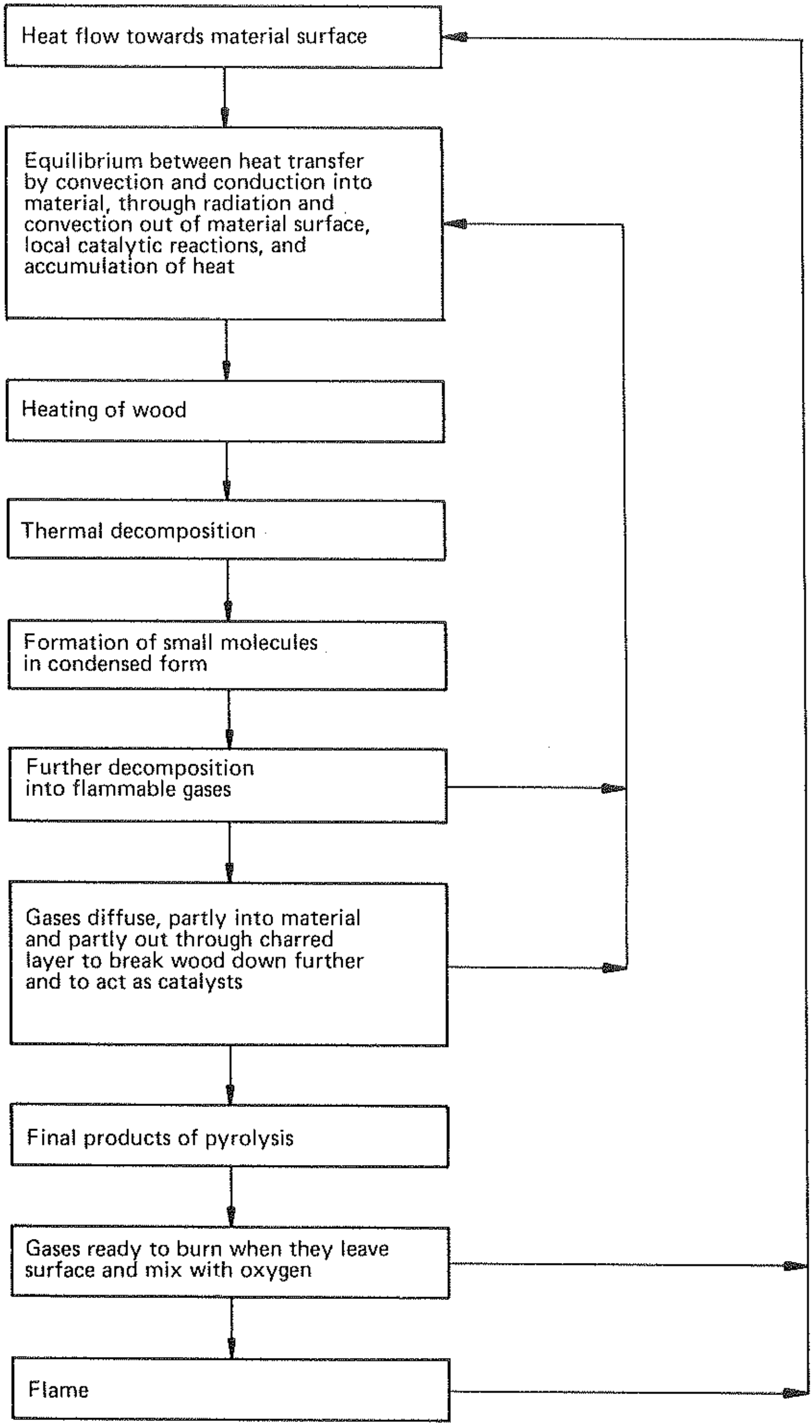
The effect due to the thickness of the charcoal layer is negligible for thicknesses greater than 6 mm /4.8, 4.9/. As permeability along the grain is 10,000 times as high as perpendicular to the grain, the test specimen must be carefully sealed. The water and the gases formed during combustion further complicate the processes by virtue of the fact that some of these leave the specimen and some are transported further into the material and condense there, perhaps to be vaporised again at a later stage. This transport, condensation and vaporisation has a pronounced effect on the temperature-time relationship inside the specimen. This has been verified in tests on wooden cylinders /4.10/.

The following material parameters should be taken into consideration in a study of the rate of charring in a timber structure exposed to fire: density, thermal conductivity and moisture ratio of the uncharred wood, the temperature at the base of the charcoal layer, the quantity of flammable gases, and the characteristics of the charcoal layer (thickness, crack size, permeability and thermal conductivity). Variables in the environment such as fire compartment temperature and the type of heat source also affect the rate of charring.

A flow chart which describes the influence of these parameters in outline is given in FIG. 4.3. It will be seen from this figure that the interacting physical and chemical processes exert a great influence, and that the sequence of events can be divided into two parts. One of these parts is associated with the inside of the material and consists of determination of the reaction products which are generated for a given thermal exposure, and for the temperature history of the specimen. The other part refers to the surface of the material and to the boundary layer situated outside this. This part consists of determination of the size and intensity of the flame at the boundary layer and of the heat transferred by the flame to the surface of the material for a given quantity and composition of the pyrolytic products which enter the boundary layer.

This problem can be solved comparatively easily in the case of a liquid fuel, since in this case vaporisation (pyrolysis) is confined to a thin layer near the surface, and only the external conditions need then be determined. The problem is more complicated in the case of solid fuels which char, since in this case the internal conditions play a critical role.

Since we know far more about dealing with heat and mass transfer problems than about dealing with chemical processes, it is natural for the rate of charring and the temperature states to be studied by solving the heat and mass balance equations, and for the influence of the chemical processes to be taken into consideration as "point sources". In studying these point sources, it



Heat flow towards material surface
Equilibrium between heat transfer by convection and conduction into material, through radiation and convection out of material surface, local catalytic reactions, and accumulation of heat
Heating of wood
Thermal decomposition
Formation of small molecules in condensed form
Further decomposition into flammable gases
Gases diffuse, partly into material and partly out through charred layer to break wood down further and to act as catalysts
Final products of pyrolysis
Gases ready to burn when they leave surface and mix with oxygen
Flame

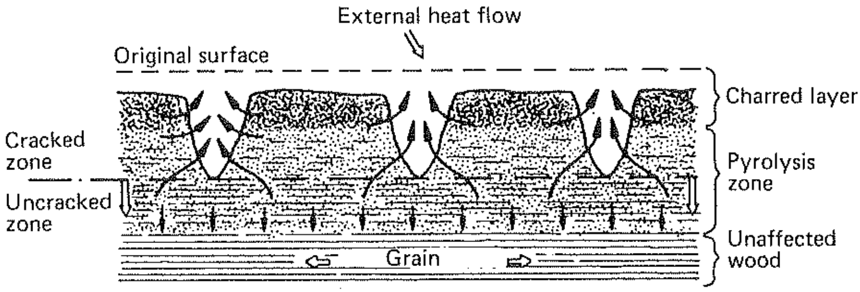
a) As the charred layer increases in thickness all the time, it will be more difficult for the products of pyrolysis to pass through the layer.

b) As a result of this increased resistance, it is possible for the flammable gases to contribute to further decomposition of the material and for them also to act as catalysts.

c) A network of cracks of a depth which increases in step with the expansion of the pyrolytic zone develops at the surface. Exchange of heat between the external heat source and the cracked zone then no longer takes place across a plane surface, but the radiant and convective heat can now be transferred directly to the uncharred wood by way of these cracks. If the grain is parallel to the irradiated surface, gases will mainly exit through the cracks, since flammable gases can be transferred most easily along the grain. This is illustrated in FIG. 4.4. The effect of these cracks reduces the effects due to a) and b) above.

d) The simultaneous and interacting chemical processes are extremely complicated, and very little is known about them at present.

e) Heating of the wood varies with temperature level and time. This means that the kinetic constants will also vary.



Full arrows show probable direction of flow of flammable gases

FIG. 4.4. Section of wood subject to pyrolysis /4.2/.

f) In the uncracked zone the flammable gases will build up to an internal excess pressure which at first increases in direct proportion to the distance from the exposed surface and then diminishes to the value applicable to the unaffected wood. As a consequence of this pressure, most of the flammable gases will flow towards the exposed surface, but a smaller portion is transported further into the wood where it

g) The coupling between heat and mass transport reduces the rate of heating inside the material /4.11/.

4.4 Mathematical models

An outline description is given in the following of the structure of a mathematical model which is intended for calculation of the non-steady temperature, moisture and density-time fields for a timber structure exposed to fire, in which the flow of heat inside the material is divided into a conductive part and a convective part, and exchange of heat at the surface of the material consists of a radiant component and a convective component. Such a model comprises the following constituents /4.1/:

a) Equations of continuity for the fundamental variables energy, moisture, gas components and mass.

b) Relations between the variables of state of the problem which, in addition to the fundamental variables according to a), comprise temperature, vapour pressure, relative humidity, saturation pressure at a given temperature, the pressure of condensed water, and pore volume.

The fundamental assumption made is that thermodynamic equilibrium exists locally at each point during the dynamic process. This implies that the gas phase, liquid phase and solid phase assume the same temperature in the immediate vicinity of the point. In addition, the whole liquid phase assumes the same pore water pressure in the immediate vicinity of the point, and all gas phases assume the appropriate gas pressure and vapour pressure in this confined region. It is further assumed that the pressure differences due to the flammable gases are negligible, so that the flammable gases are free to move out of the pore system, i.e. there is no change in pyrolytic concentration.

c) Expressions for the flows of energy, moisture and flammable gases. These expressions must be formulated in such a way that the flows at an arbitrarily selected point in time can be calculated from the distribution of temperature, moisture etc in the wood.

The flow of energy is complicated by the mass flow which, in addition to thermal conduction, contributes to the total flow of energy. The total flow can be described as a convective component which defines the energy content per unit mass of flammable gases and moisture, and a conductive component for which the thermal conductivity is a function of temperature, moisture content and density. Treatment of moisture flow is very complicated owing lysis of wood is particularly complicated, and this may explain why it has been the subject of only a few studies. Fredlund /4.1/ presents a mathematical model which has not, however, been verified experimentally, and in other investigations only the distribution of moisture in test specimens exposed to fire has been measured /4.6, 4.13, 4.14/. If it is further assumed that the pressure differences due to the flammable gases are negligible, the rate of flow of these is given by the rate of production of flammable gases.

d) Expressions for the production terms which describe the energy released per unit time, and the change of phase which occurs during pyrolysis. This change of phase is usually assumed to mean decomposition of the wood into flammable gases and water. The production terms are related to the rate at which wood undergoes pyrolysis. Pyrolysis is governed by complicated chemical reactions. On the assumption that most of the chemical reactions in the wood consist of decomposition of molecules independently of the presence of other molecules, and that the chemical reactions are affected to the same extent by the temperature, a "mean reaction" for the pyrolysis of wood may be considered to conform to an Arrhenius function. If the heat of reaction of wood is known, the energy released during pyrolysis can also be given.

e) Boundary and initial conditions which have been discussed briefly in the foregoing.

As a complement to a more complete mathematical model of the character described above, it is desirable to have access to a simplified model which can be used for rapid estimation of the rate of charring of a material. Such a model has recently been presented by Delichatsios and de Ris /4.15/. This model comprises a simple analytical solution for calculation of the asymptotic rate of pyrolysis for charring materials which are exposed to a constant external radiation. Together with the results of a few laboratory experiments, this model provides a satisfactory basis for the simple approximate prediction of the rate of charring of a material in a real fire environment.

The analytical solution assumes that heat transfer in the charred layer and in the flammable gases can be ignored in relation to heat transfer in the unaffected material. It is further assumed that the process of pyrolysis can be described in terms of constant temperature and heat of reaction, i.e. without application of an Arrhenius function. This assumption has been verified by long experience of simple homogeneous materials.For wood and wood based materials which are characterised during a fire by the formation of a permanent charred layer which gradually reduces the rate of pyrolysis, this assumption represents a crude approximation.

4.5 Conclusions

From the above, the following appear as urgent research projects:

1) For thin walled timber structures

Development of a simplified one-dimensional model for calculation of the rate of charring and temperature distribution. Consideration must be given in this context to the reaction kinetics parameters of wood, which requires extensive experimental studies.

2) For timber structures comprising solid sections

Development of a simplified one-dimensional model for calculation of the rate of charring, temperature gradient and moisture distribution. This task can be solved without recourse to complicated combustion equations. Treatment must include transfer processes, and this requires a simplified model for moisture transfer in the material, and experimental determination of a number of material constants.

In a second stage, it is natural to develop such a model into a two and three dimensional one, so that it may have practical application for beams and different types of splices and connections.Such a process must take account of the anisotropic properties of wood.

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5. MECHANICAL PROPERTIES

5.1 Introduction

Optimum design of loadbearing timber structures which are exposed to fire requires methods which take into consideration the assumptions made concerning loading and thermal exposure. Section 6.1 describes existing design methods for beams and columns which - depending on the degree of thermal exposure selected - provide a more or less rough estimate of loadbearing capacity and real fire resistance. These methods normally yield results which are probably very considerably on the safe side. Application of these methods is confined to calculation of limiting bending moments and critical loads for certain types of instability phenomena. Calculation of deformations is not possible by means of these methods.

Methods which are to be of more general application and also form the foundation of optimum design must be based on experimentally verified analytical models which give a functionally correct description of the different processes involved in the thermal and mechanical behaviour of the structure in the event of fire. For optimum design, the design method must further be coupled to a probabilistic analysis according to Section 1.5.

One of the requirements for advanced calculation of the loadbearing capacity of a structure under fire exposure conditions is an experimentally verified material model in which the mechanical properties of wood are described as functions of the transient stress, temperature and moisture states. When such a material model is available, a structural calculation can be carried out concerning the behaviour of the construction at any time during the fire with respect, inter alia, to temporal variations in forces, moments and stresses due to internal and external constraints.

5.2 Strength and deformation properties

Existing knowledge concerning the mechanical properties of wood derives mainly from tests on small specimens. However, a large body of information obtained by extensive tests of this type provides only a limited basis for practical design, since in these tests the strength properties are determined on wood without any defects. It has been shown with regard to bending resistance that the stresses in the compression zone are critical for small specimens without defects, while it is the stresses in the tension zone which are crucial for structural elemore in line with a Weibull distribution, which shows that the strength of structural timber is governed by brittle failure.

Existing knowledge of the mechanical properties of wood is mainly derived from investigations carried out at constant temperature and moisture, either at constant stress levels or at stresses subject to different temporal variation patterns, while in a real fire situation temperatures and moisture contents are transient. These investigations thus provide information concerning the variation in strength and deformation properties for different combinations of steady temperature and moisture levels.

Wood has a very complex anisotropic structure, is subject to wide variation in quality within the same species of timber, and has different types of defect. This makes it difficult to summarise variation in mechanical properties due to different types of exposure.

The instantaneous moduli of elasticity and strength values relating to different loading directions increase both when the moisture ratio decreases below the fibre saturation point and when the temperature drops. This is shown for wood loaded parallel to the grain in FIG. 5.1, 5.2, 5.3 and 5.4, taken from Gerhards /5.1/. The captions refer to the sources from which the results are taken.

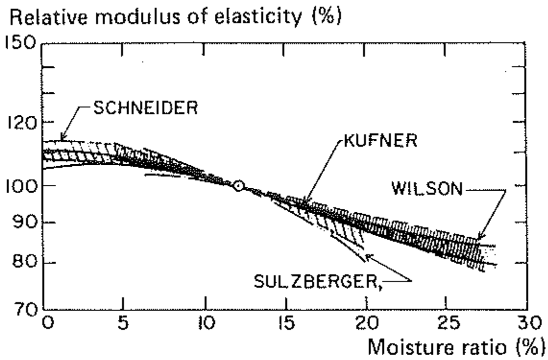

FIG. 5.1. Effect of variable moisture ratio on the modulus of elasticity parallel to the grain at 20°C. The value at 12°C is taken to be 100%. /5.1/.

It will be seen from the figures that for temperature levels above 100°C there are no results concerning bending resistance. Such values are however available for tures, but these results are taken from investigations on cellulosic fibres heated over periods of only a few seconds.

The periods of exposure which are of interest for a timber structure exposed to fire are 1-2 hours. This means that the long-term effect given in the literature, creep up to failure, is not relevant for timber structures under fire exposure conditions at normal stress levels. In such cases the stress level chiefly influences the proportionality of the creep curve, the magnitude of creep and the modulus of elasticity of wood. Other important factors which govern deformations are temperature and moisture ratio. It is clear from reported transient tests that the deformation which occurs in a specimen for a defined combination of stress and temperature is dependent on the stress and temperature history /5.2, 5.7/.

At a given stress level, higher temperatures and higher moisture ratios generally result in greater deformation /5.3, 5.4/. A change in moisture ratio at a load likely to occur under fire exposure conditions has a considerable effect on deformation, as shown, inter alia, by Armstrong and Kingston /5.5/. Perkitny claims that changes in moisture ratio as small as 1% exert an appreciable effect on creep /5.6/.

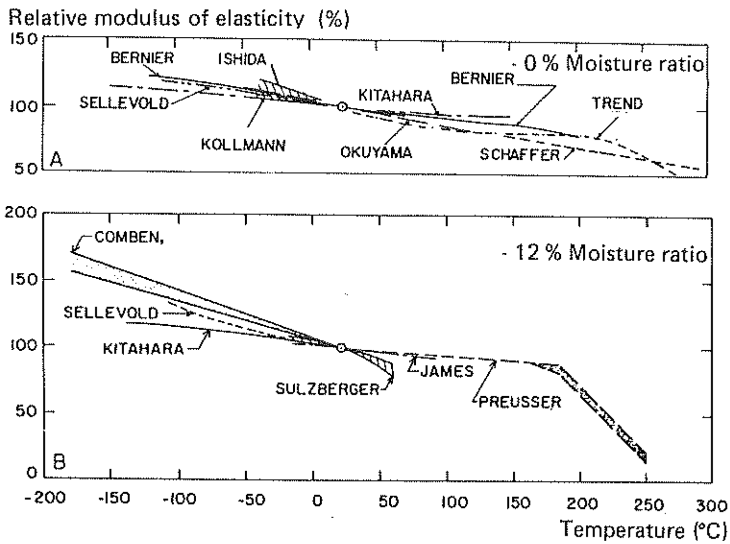

FIG. 5.2. Effect of variable temperature on the modulus of elasticity parallel to the grain. A: Mois-

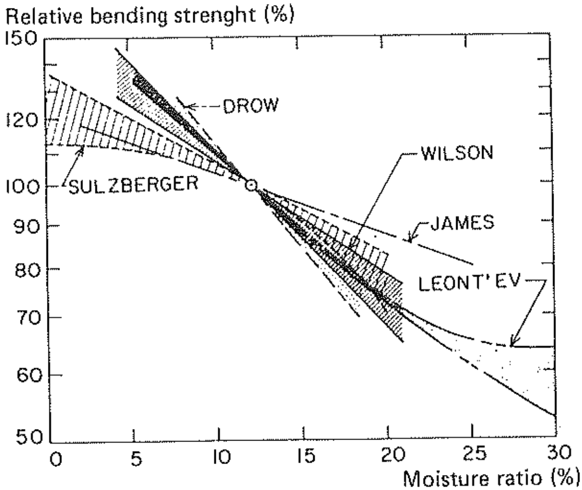

FIG. 5.3. Effect of variable moisture ratio on bending resistance at 20°C. The value at 12% moisture content is taken to be 100% /5.1/.

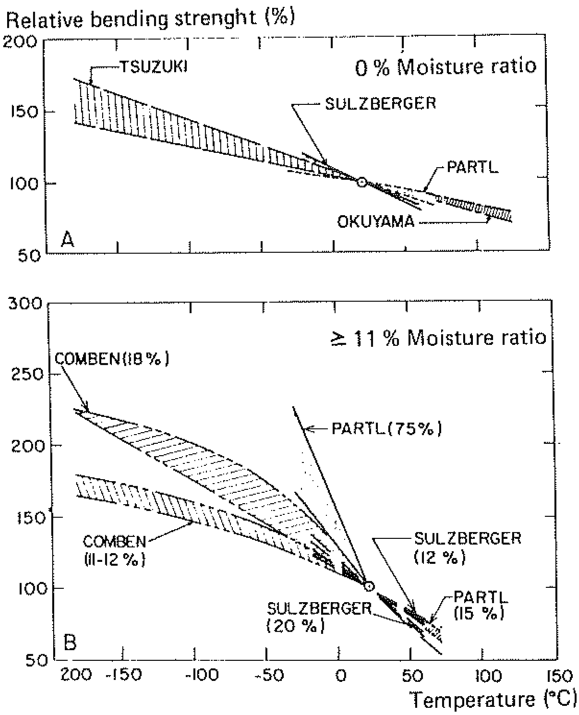

FIG. 5.4. Effect of variable temperature on bending resistance. A: Moisture ratio 0%, B: Moisture

Summaries of test results relating to the mechanical properties of wood at different temperature and moisture levels are consistently characterised by wide scatter. This is due to the fact that a large number of different timber species have been used in the investigations, and to the difficulties encountered in measuring temperature and moisture ratio. The fact that in wood the moisture ratio changes with temperature makes precise definition of state difficult.

5.3 Conclusions

Reference has been made in the foregoing to the differences in data obtained concerning the mechanical properties of wood in tests on small defect-free specimens and in tests on structural elements of timber of ordinary dimensions. Future codes for timber structures will increasingly take these factors into consideration in conjunction with design at normal temperatures. It is essential that when data for these codes are produced, the specific problems associated with design methods for timber structures exposed to fire should be included.

On the basis of the experimental investigations on small specimens at variable temperature and moisture conditions a number of crude material models have been developed for the mechanical behaviour of wood, but there is none in which consideration is given to the deformations due to transient stresses and temperatures and the simultaneous presence of moisture. It is therefore essential that such an analytical model, suitable for advanced calculations, should be developed. This model must be capable of use for practical calculations of the deformations and instability loads in timber structures exposed to fire. Validity of this model must be verified by experimental studies on small specimens and, finally, also on some larger specimens such as beams in flexure and columns under axial compression.

Nothing has been published as to why temperature and moisture modify the mechanical properties, only the way in which these change. It is therefore important to ascertain whether the biological differences between different species or within the same species can phenomenologically explain some of the great scatter in result relating to the mechanical properties of wood at defined combinations of temperature and moisture ratio. Such an investigation should include development of a simplified analytical model which takes into consideration the growth ring structure of wood and the relationship between cellulose and lignin.

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6. FIRE BEHAVIOUR OF STRUCTURAL ELEMENTS AND STRUCTURES

The overriding object of advanced design of loadbearing and separating constructions must be that the design is based on realistic assumptions concerning fire exposure and loading, and that it produces structures which have a uniform and reasonable level of safety in combination with satisfactory overall economy.

The methods which are normally applied at present for the determination of the behaviour and limit states of a timber structure exposed to fire permit only rough assessments. The inescapable consequence of this in practical design if the production of design solutions of greatly variable safety level at a cost which can be very far from the optimum.

In Sweden, extensive research has been carried out concerning the fire behaviour and design of steel and concrete structures. In conjunction with this, an entirely new design procedure has been developed. For steel structures exposed to fire, the research results have been summarised in a manual which has been granted type approval by the Swedish Board of Physical Planning and Building /1.12, 1.13/. As regards concrete structures under fire exposure conditions, research and development is in progress at the Division of Building Fire Safety and Technology, Lund Institute of Technology with the aim of producing a similar design manual /1.21/. The design procedure is based on conditions during real fires and is well suited for adaptation to modern loading and safety principles. The method also results in a more uniform safety level and reduced costs in relation to those obtained by means of the highly schematic methods which are internationally predominant.

Research which may result in a similar functionally based design procedure for timber structures exposed to fire is of urgent necessity, and is essential if steel, concrete and timber are to compete in the future on equal terms as materials for loadbearing and separating constructions.

In Section 6.1, a description is given of the calculation procedure for a functionally based design method related to actual fire conditions. The present state of knowledge and the practical conditions for application of this method are touched upon in outline with reference to structures of solid section, for instance glued laminated structures. In Section 6.2 a similar assessment is made concerning lightweight and composite timber structures with a loadbearing and/or separating function. Finally, in Section 6.3, the problems which are specific to fire design of splices,attachments and connections are dealt with.

6.1 Timber structures of solid section

The characteristics applicable to fire in a fire compartment are of fundamental importance for analytical fire design of loadbearing and separating structures. The critical input parameters are as follows /6.1/ - see FIG. 6.1.

(1) The design value of the fire load intensity,

(2) the combustion properties of the fire load,

(3) the size and geometry of the fire compartment,

(4) the ventilation conditions in the fire compartment,

(5) the thermal properties of the constructions enclosing the fire compartment.

These parameters together determine the rate of combustion and the energy released per unit time, and the design gas temperature-time curve of the fire compartment for an undisturbed fire sequence.

Together with

(6) the structural data of the structure,

(7) the thermal, moisture mechanics and combustion properties of the structural material,

(8) the surface heat transfer conditions and the combustion characteristics for the boundary layer,

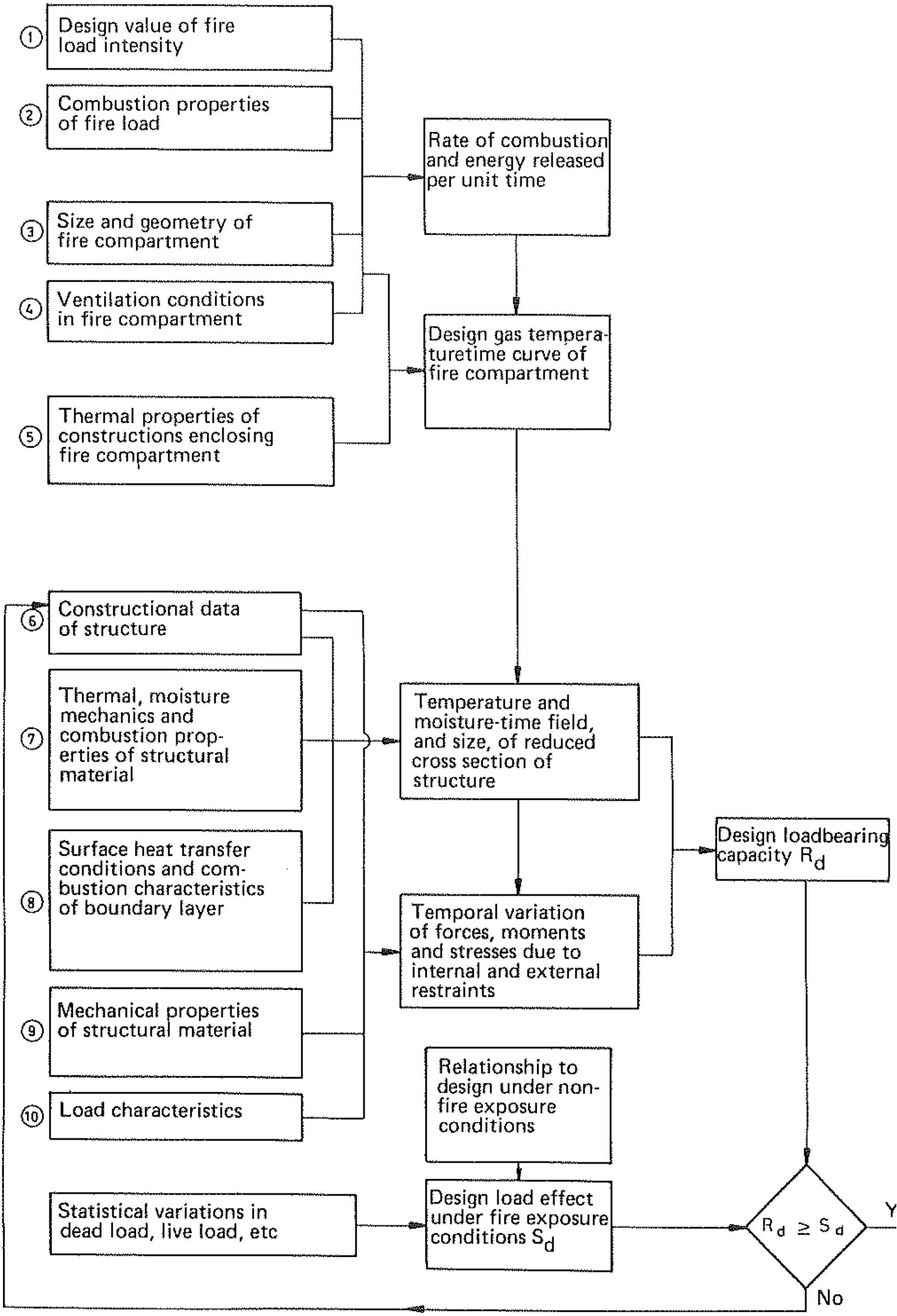
this curve defines, for a structure of combustible material, the temperature and moisture fields and the reduced cross section of the fire-exposed structure and its components at every point in time of the fire sequence. With

(9) the mechanical properties of the structural material

(10) load characteristics

as further input parameters, the forces, moments and stresses which occur in the fire-exposed structure due to internal and external restraints on deformation which may be present, and the temporal variation of the loadbearing capacity of the structure, can be determined. The smallest value of this loadbearing capacity during the complete fire sequence defines the design loadbearing capacity R_d of the structure.

On the basis of characteristic values, partial coefficients and load reduction factors relating to dead load, live load etc, selected in view of the fact that fire exposure is to be regarded as an accidental load, the design load effect in the event of fire, S_d, is defined /6.2/. Direct comparison of the design loadbearing capacity R_d and the design load effect S_d then determines

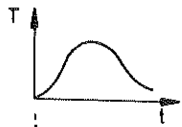


1 Design value of fire load intensity
2 Combustion properties of fire load
3 Size and geometry of fire compartment
4 Ventilation conditions in fire compartment
5 Thermal properties of constructions enclosing fire compartment
Rate of combustion and energy released per unit time
Design gas temperaturetime curve of fire compartment
6 Constructional data of structure
7 Thermal, moisture mechanics and combustion properties of structural material
8 Surface heat transfer conditions and combustion characteristics of boundary layer
9 Mechanical properties of structural material
10 Load characteristics
Temperature and moisture-time field, and size, of reduced cross section of structure
Temporal variation of forces, moments and stresses due to internal and external restraints
Design loadbearing capacity R_d
Relationship to design under non-fire exposure conditions
Statistical variations in dead load, live load, etc
Design load effect under fire exposure conditions S_d
$R_d \geq S_d$
No
Y

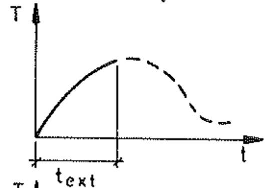
For purposes of design, the gas temperature-time curve of the fire compartment can be selected either according to /6.1/, Section 3.2 (Method I) - as exemplified in FIG. 1.2 - or it can be determined in each individual case on the basis of the energy and mass balance equations of the fire compartment or in some other equivalent manner, for instance experimentally or by a combined experimental and theoretical method (Method II). The fire characteristics according to Method I assume a fire compartment of a size applicable, for instance, to dwellings, ordinary offices, schools, hospitals, hotels and libraries. For fire compartments of very large volume - for instance industrial and sports premises - the data produced by Method I provide a very poor representation of a real fire exposure. This also applies for the gas temperature-time curve which is used in conjunction with standardised fire tests according to ISO 834. At present there is no well substantiated body of data available which permits more accurate fire design of fire compartments of large volume - see also the comments on p. 11

The design fire load and the characteristics of the fire compartment thus form the basis for determination of the design fire exposure, expressed in terms of the design gas temperature-time curve of the fire compartment, which is used as input in the flow chart in FIG. 6.1. Depending on practical application, the design loadbearing capacity may be required for

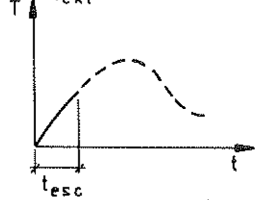
a) a complete fire sequence



b) part of the fire sequence, t_{ext}, determined with respect to the time needed for fire fighting in unfavourable conditions



c) part of the fire sequence, limited by the design escape time t_{esc} from the building.



The provision of an automatic fire extinguishing system can be taken into consideration in selecting the design fire load. This is also affected, for instance, by the consequences of failure in the loadbearing structure with respect to injuries to persons or damage to property.

The time for which retention of loadbearing capacity is to be specified must be judged in each case. It is quite tive a), results in comparatively large savings in cost owing to the smaller dimensions of the loadbearing system. Apart from the requirements specified in the regulations,one of the factors which are critical for the choice of the alternative to be used as the basis of design are the economic judgments made by the owner of the building. The value of the building, the value of its contents, the costs due to loss of production, the clearance and repair costs etc are all relevant to such a judgment.

The feasibility of applying the design method described in FIG. 6.1 is commented on in the following with reference to a timber structure of solid section such as a glued laminated structure.

6.1.1 Rate of charring

Design may, for instance, be based on experimentally determined relationships between the thickness of the charred layer and the duration of fire exposure. FIG. 6.2 illustrates such a relationship for the thermal exposure applicable for standardised fire tests according to ISO 834 - Equation (1.1).

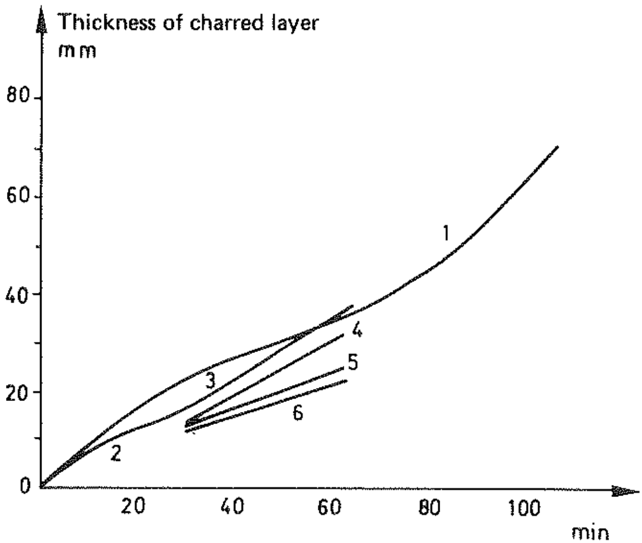


FIG. 6.2. Experimentally determined relationship between the thickness of the charred layer and the

On the basis of the curves in FIG. 6.2 and the results of similar investigations, the rate of charring which is representative for thermal exposure according to ISO 834 is often taken to be 0.6 mm/min. /6.18 and 6.19/ quote corresponding figures which are appreciably more conservative. The rate of charring applied for columns is 0.7 mm/min, and for beams it is 0.8 mm/min for the vertical and upper horizontal surfaces, and 1.1 mm/min for the soffit. These figures have been adopted in DIN 4102, Part 2.

For fire design of timber structures for a differentiated fire sequence, with the gas temperature-time curves in accordance with FIG. 1.2, the Commentary to SBN 1976:1 recommends the curve in FIG. 6.3 as the provisional basis for the rate of charring - see also /6.7/ and /6.13/. This approximate curve has been drawn on the basis of a study of investigations reported by Knublauch /6.8/. The duration of fire is estimated to be the time up to the point where the downward branch of the appropriate gas temperature-time curve has dropped to 300°C.

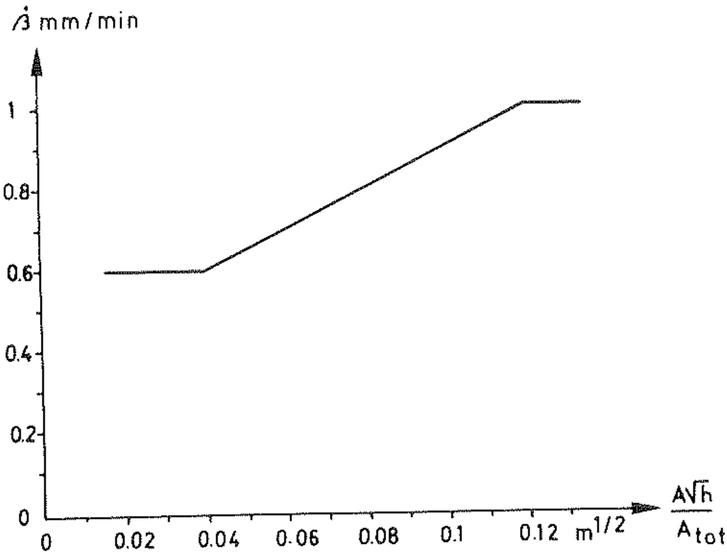


FIG. 6.3. Approximate relationship constructed on the basis of simplified considerations for the rate of charring β of solid or laminated timber beams of pine or spruce as a function of the opening factor $A\sqrt{h}/A_{tot}$ of the fire compartment /6.1, 6.7, 6.13/.

A simplified analytical model for calculation of the depth of the charred layer under variable thermal exposdiagrams and approximate formulae for calculation of the depth (mm) of the charred layer in laminated structures exposed to fire in conformity with the gas temperature-time curve according to FIG. 1.2. The following approximate formulae apply:

$$\theta = \frac{0.0175f}{\frac{A\sqrt{h}}{A_{tot}}} \tag{6.1}$$

$$\beta_o = 1.25 - \frac{0.035}{\frac{A\sqrt{h}}{A_{tot}} + 0.021} \tag{6.2}$$

$$\left.\begin{aligned} \beta &= \beta_o t && \text{for } 0 \le t \le \frac{\theta}{3} \\ \beta &= \beta_o\left(-\frac{\theta}{12} + \frac{3t}{2} - \frac{3t^2}{4\theta}\right) && \text{for } \frac{\theta}{3} \le t \le \theta \end{aligned}\right\} \tag{6.3}$$

where

f = fire load intensity, MJ/m^2 of enclosing surface
$A\sqrt{h}/A_{tot}$ = opening factor of fire compartment, $m^{1/2}$
θ = time in minutes at which maximum charring rate occurs for the fire load intensity and opening factor concerned
β_o = initial value, mm/min, of the rate of charring
t = elapsed time in minutes.

The model in /6.9/ provides no information concerning temperature and moisture distribution in the uncharred portion of the timber section.

Fredlund /6.11/ gives a model for the pyrolysis of wood which is of more general application and is also functionally superior to the models given in the literature. This model provides data for calculation of the rate of charring under variable real conditions during the early stages of a fire and for a fully developed fire. The publication also outlines methods for approximate determination of the temperature and moisture states in timber structures. Further development is however needed before this method is easy to apply in practice.

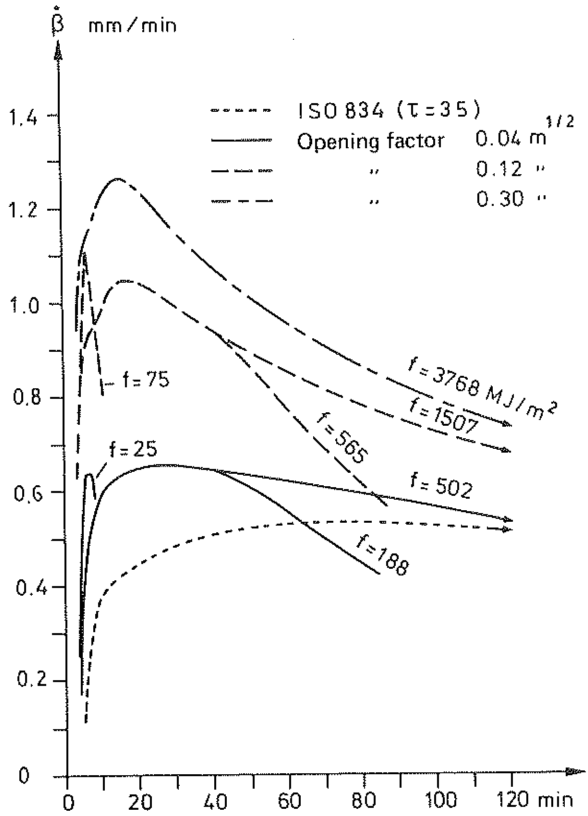


FIG. 6.4. Mean rate of charring $\dot{\beta}$ as a function of fire duration for thermal exposure according to the standard fire curve (ISO 834), corrected for a furnace with the characteristic time τ = 35 minutes, for different gas temperature-time relationships expressed in terms of the fire load intensity f and the opening factor

6.1.2 Beams in a limit state in the form of flexural failure

On the assumption that the thickness β of a charred layer during the relevant part of the fire sequence can be determined according to Equations (6.1) - (6.3), and that the change in mechanical properties of the uncharred material under fire exposure conditions can be described as a reduction of ultimate stress by a factor μ, relationships can be derived for the loadbearing capacity of a cross section exposed to fire on three or four sides.

FIG. 6.5 and 6.6 set out such curves for fire exposure on four and three sides respectively. The curves give the value of the ratio β/B corresponding to flexural the cross section with respect to failure in pure bending prior to fire exposure. For the region β/B > 0.25 the curves are shown dashed, as for this region the design assumptions have not been sufficiently verified experimentally. The factor μ which describes the reduced loadbearing capacity of the uncharred part of the cross section with respect to elevated temperature and increased moisture content during the fire has been given the value 0.8.

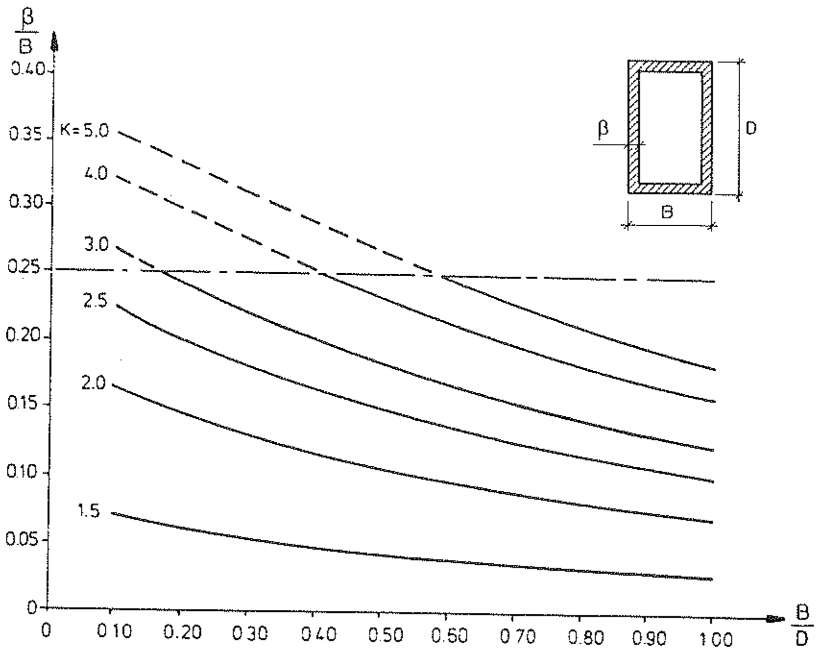


FIG. 6.5. Curves showing the relationship between the ratio β/B and the width/depth ratio B/D of the cross section for a solid or laminated timber beam of rectangular cross section which is exposed to fire on four sides. The curves are drawn on the assumption of flexural failure. K is the factor of safety of the cross section prior to fire exposure /6.13/.

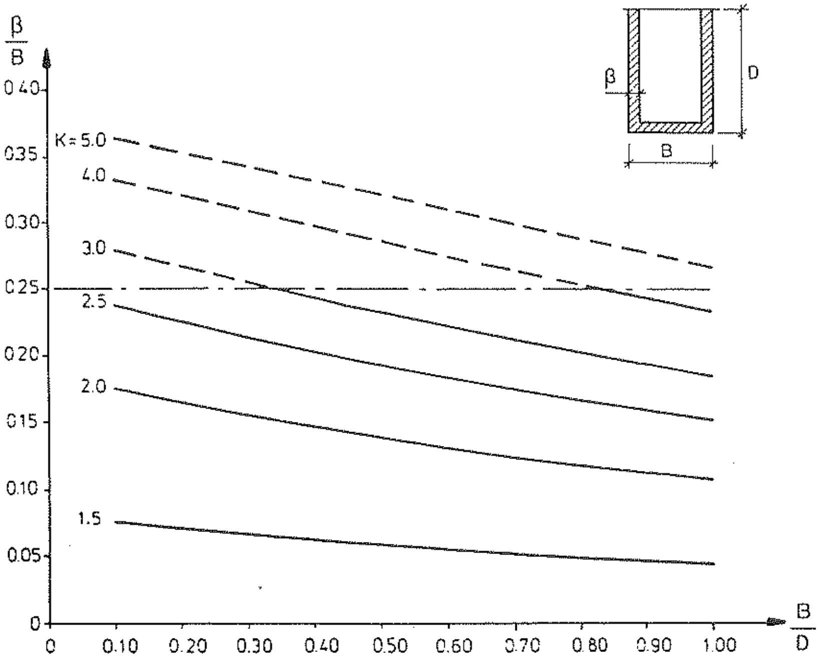


FIG. 6.6. Curves showing the relationship between the ratio β/B and the width/depth ratio B/D of the cross section for a solid or laminated timber beam of rectangular cross section which is exposed to fire on three sides. The curves are drawn on the assumption of flexural failure. K is the factor of safety of the cross section prior to fire exposure /6.13/.

6.1.3 Beams in a limit state in the form of instability failure

If the risk of lateral torsional instability must be considered, the problem is complicated by the fact that the critical load gradually diminishes during the fire owing to progressive reduction of the cross section and the consequent increase in slenderness ratio. The risk is further accentuated if lateral stiffeners collapse or vanish during the fire.

/6.12/ gives an extensive body of data for the design of rectangular timber beams under fire exposure conditions with respect to the risk of lateral torsional instability. To sum up, this design comprises the following stages:

The unburned part of the cross section is determined in section. The time up to failure is defined as the time that elapses until the stresses attain a certain value, depending on slenderness, which is defined by the formula

$$\alpha = \sqrt{\left\{\frac{\sigma_{bk}}{\sigma_E}\right\}} \qquad (6.4)$$

where σ_{bk} is a characteristic value of the ultimate flexural stress calculated on the assumption of linear stress distribution. The Swedish Building Code SBN 1980 specifies the value $\sigma_{bk} = 3\sigma_{ma}$, where σ_{ma} is the permissible compressive stress in bending. σ_E is the maximum compressive stress in bending due to the critical lateral torsional load calculated according to the elastic theory. The permissible compressive stress in bending, σ_{ma}, is reduced with respect to lateral torsional failure by multiplication by the factor $\kappa_v(\alpha)$ which has the following values:

$$\left.\begin{aligned} \kappa_v(\alpha) &= 1 && \text{when } \alpha \leq 0.6 \\ \kappa_v(\alpha) &= 1.37 - 0.61\alpha && \text{when } 0.6 < \alpha \leq 1.4 \\ \kappa_v(\alpha) &= 1/\alpha^2 && \text{when } \alpha > 1.4 \end{aligned}\right\} \qquad (6.5)$$

A subsidiary condition is that the least lateral dimension of the beam should not, initially, be less than 4 times the maximum depth of penetration of the charred layer.

Once the value of the thickness β of the charred layer is known during the relevant part of the fire sequence, then, according to the technique described above, an expression can be derived for the critical value of the ratio β/B as a function of K, B/D and a parameter η which expresses the sensitivity to lateral torsional failure of a beam which is not exposed to fire. This parameter is defined as

$$\eta = \sqrt{\frac{LD}{mB^2}} \qquad (6.6)$$

where L is the length of the beam and m is a coefficient which depends on the load on the beam and its end restraint conditions and which, for normal practical applications, can be obtained from manuals.

FIG. 6.7 and 6.8 give examples of solutions for the case

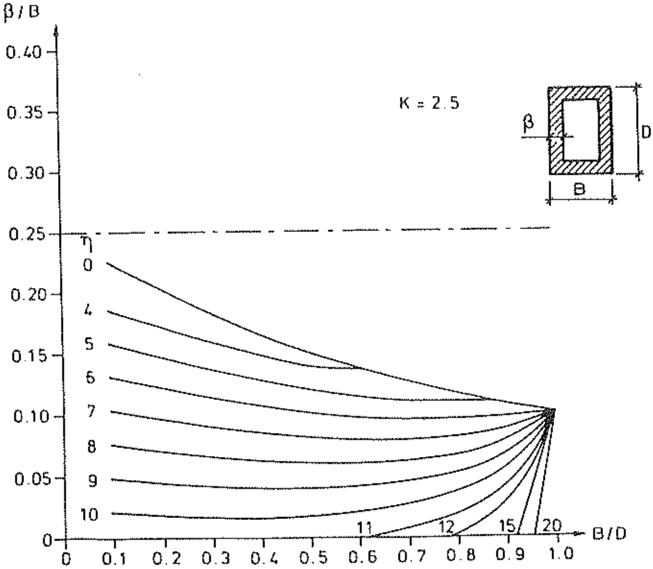


FIG. 6.7. The ratio β/B as a function of the width/depth ratio B/D for beams exposed to fire on four sides, for different values of the parameter η and for K = 2.5 where K is the factor of safety with respect to flexural failure prior to the fire /6.12/.

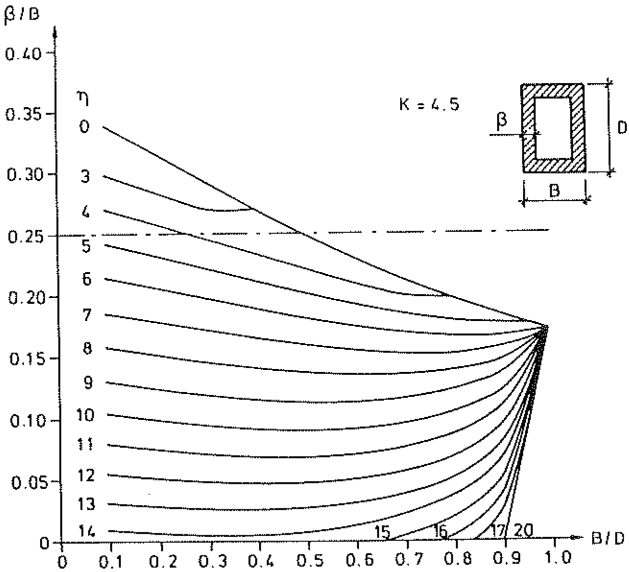


FIG. 6.8. The ratio β/B as a function of the width/depth ratio B/D for beams exposed to fire on four sides, for different values of the parameter η and for K = 4.5

6.1.4 Columns in a limit state in the form of buckling

In designing columns where there is no risk of buckling, the same procedure can be applied as for beams. If the risk of buckling must be taken into consideration, the problem is complicated by the fact that this risk increases during the entire fire sequence owing to the progressive reduction in cross section and the consequent increase in slenderness ratio.

The unburned part of the cross section is determined in the same way as for beams according to Subsection 6.1.1. The slenderness ratio and the stresses are calculated for the reduced cross section. The time up to failure is defined as the time that elapses until the stresses have attained a certain value which depends on the slenderness ratio. According to /6.13/, this value can be permitted to attain twice the value permissible for the stress for an ordinary combination of loads. A subsidiary condition is that the slenderness ratio shall not exceed 170, and that the least initial lateral dimension of the cross section shall not be smaller than four times the maximum depth of charring.

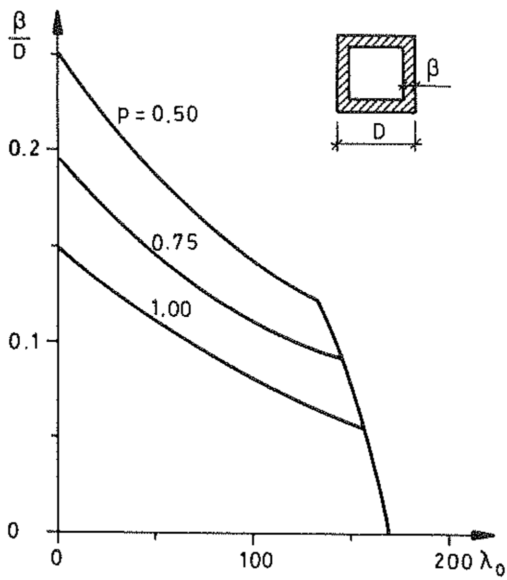


FIG. 6.9. Curves for determination of the thickness β of the charred layer corresponding to buckling for different values of the initial slenderness

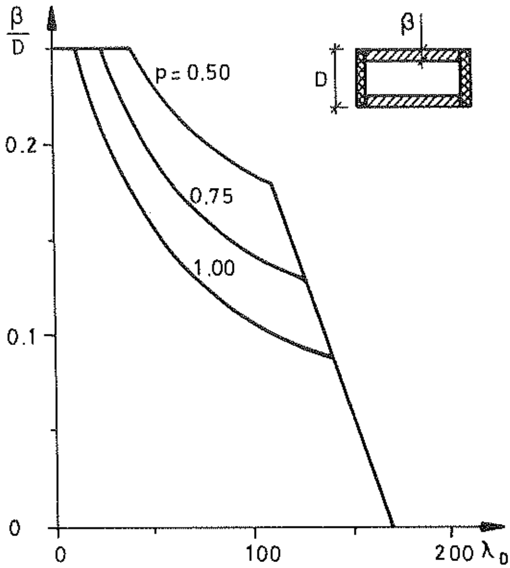


FIG. 6.10. The same curves as in FIG. 6.9, but applicable to the case where the fire can attack the section only on two opposed sides. It is assumed that buckling occurs at right angles to the surfaces exposed to fire /6.13/.

When the thickness β of the charred layer has been determined according to Equations (6.1) - (6.3), the relationships according to FIG. 6.9 and 6.10 can be calculated on the basis of these assumptions. From FIG. 6.9, the thickness of the charred layer corresponding to failure can be determined for a column of square cross section which is exposed to fire on all four sides as a function of the initial slenderness ratio λ_0 and the ratio p of the applied load to the load permitted for an ordinary combination of loads. FIG. 6.10 presents the same curves for the case when fire can attack the cross section only on two opposed sides, buckling being assumed to occur at right angles to the sides exposed to fire.

6.1.5 Conclusions

The design method described for laminated timber structures exposed to fire is based on simplified assumptions for all the components of the method. In consequence, applicability of the method is confined to approximate calculations, which however represents considerable progress in relation to conventional design based on fire classification and the results of standard fire tests.

perties, temperature and moisture conditions, and mechanical properties. Improved knowledge of these components will permit a more meaningful and substantiated theoretical analysis of the behaviour and loadbearing capacity of different types of loadbearing timber structures under fire exposure conditions. These structures may be either directly exposed to fire, or exposed only after a certain time has elapsed since the outbreak of fire. The modes of failure which are of interest are bending, shearing, torsion, buckling, lateral torsional buckling. Analysis of the behaviour of nailed and bolted connections should be included, together with design which will give these the same strength as the rest of the fire-exposed structure. This is commented in greater detail in Section 6.3.

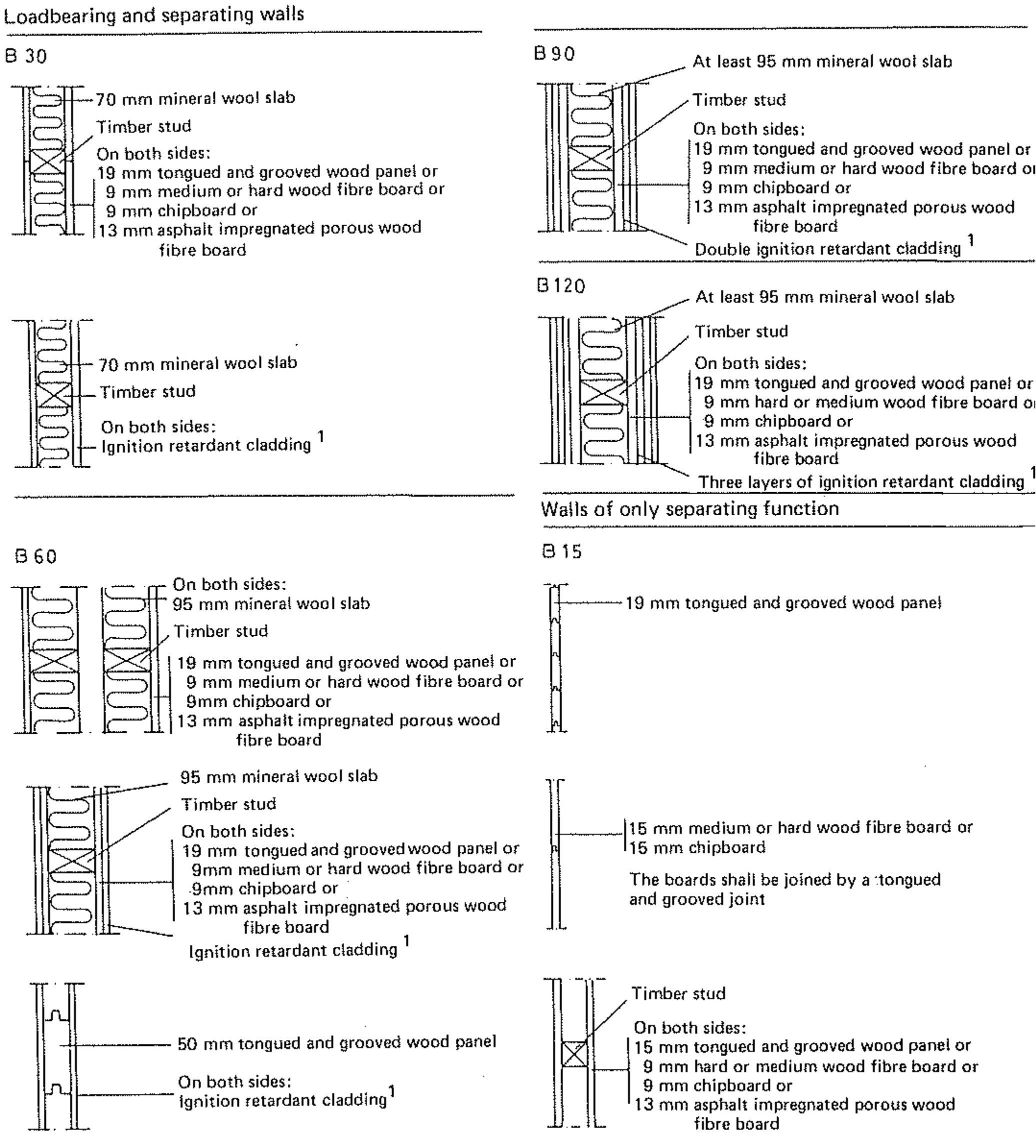
The structural analysis described above is made easier by the existence of software for high temperature structural mechanical calculations, primarily developed for concrete and steel structures.

6.2 Lightweight and composite timber structures

With regard to lightweight and composite timber structures with a loadbearing and/or separating function, subject to the action of fire, the present state of knowledge is mainly confined to the results of standard fire tests and summaries of such tests in the literature. In Sweden, type approved structures for different fire classes are listed in Approval List B published by the Swedish Board of Physical Planning and Building. An extract from this is given in /6.15/ with regard to type approved wall and floor structures of timber and/or wood based materials - FIG. 6.11 and 6.12. The most comprehensive international summaries of the results of standard fire tests and associated fire classifications are given in /6.14/ and /6.19/.

All the results published with regard to the behaviour and loadbearing capacity during a fire of lightweight and composite structures of timber relate to thermal exposure in conformity with a standard fire test - ISO 834, Equation (1.1). There are no experimental results available which illustrate the behaviour and loadbearing capacity in relation to exposure more representative of a natural fire. Nor have any analytical methods been developed for the fire design of these types of structure.

Research which may result in the development of such analytical methods is therefore of great urgency. This applies both for thermal exposure according to ISO 834 and for real exposure, described, for instance, by the gas temperature-time curves given in FIG. 1.2. Such a development would include experimental studies at full



[1] Ignition retardant cladding may be 10-13 mm gypsum plasterboard or 12 mm wood fibre board with a mineral surface layer of approved type "approved as cladding on internal wall and ceiling surfaces which is equivalent to cladding of non-combustible material", See also Approval List B published by the Swedish Board of Physical Planning and Building.

FIG. 6.11. Walls of timber and/or wood based materials granted type approval for different fire classes. For further constructional details, reference should be made to /6.15/.

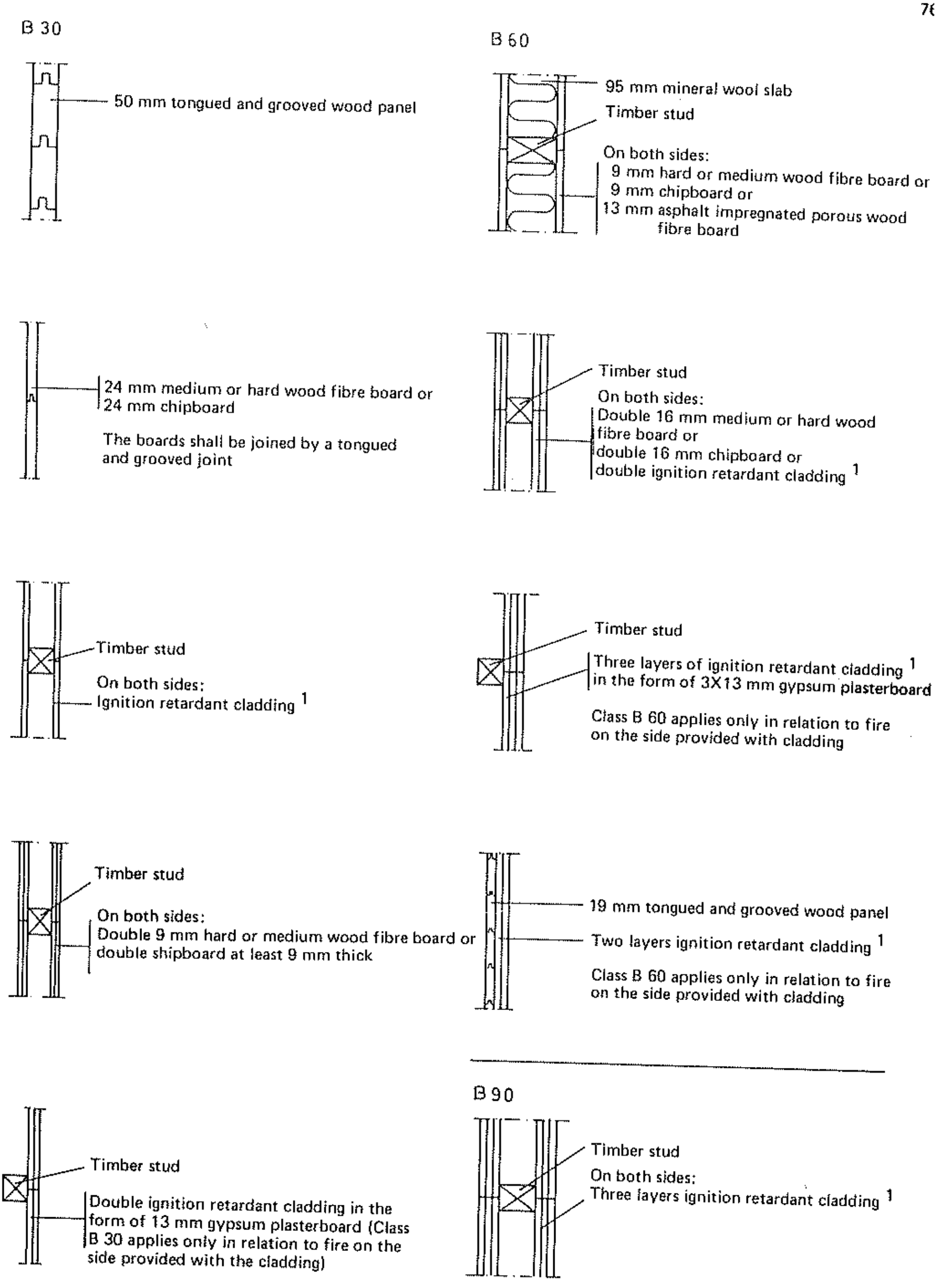


FIG. 6.11 (continued)

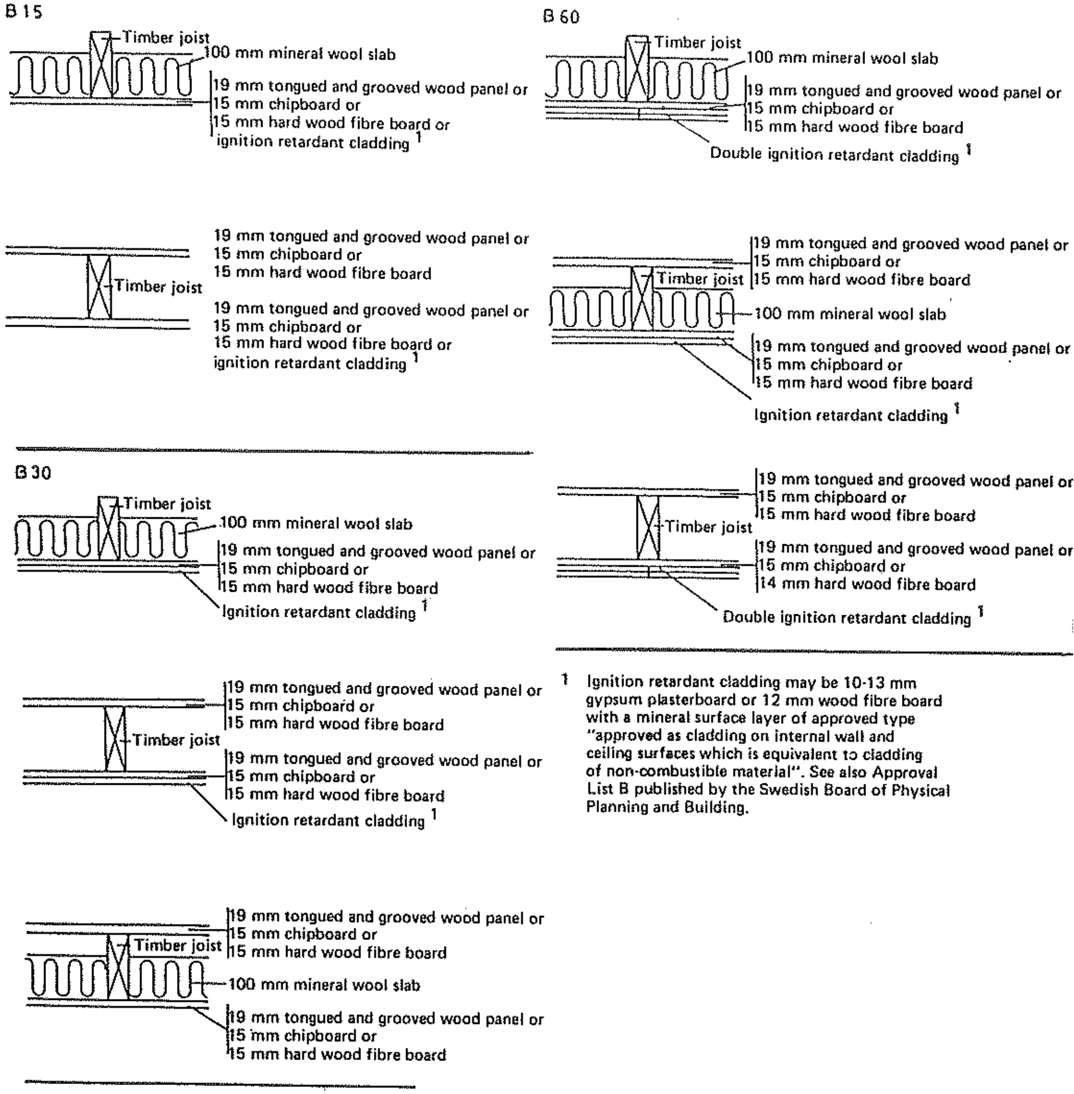


FIG. 6.12. Floor constructions of timber and/or wood based materials granted type approval for different fire classes. For further constructional details, reference should be made to /6.15/.

thin panels of wood and wood based materials under different kinds of thermal exposure - FIG. 6.13 /6.14/. Another important and urgent research project in this field is theoretical and experimental study of the possibility of increasing the fire resistance of lightweight and composite timber structures by means of fire retardant finishes.

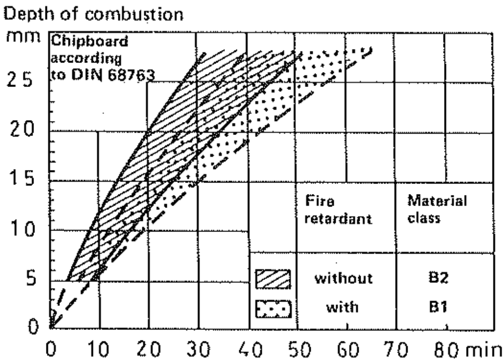


FIG. 6.13. Range of variation of experimentally determined depth of combustion for chipboard of density ≥ 600 kg/m³ when subject to thermal exposure according to a standard fire test, ISO 834 /6.14/.

6.3 Splices, attachments and connections

In loadbearing timber structures, splices, attachments and connections are critical details which demand particular attention in conjunction with design and sizing for fire exposure. The overriding requirement in this respect which is specified in Finnish building regulations reads: "Metal components which constitute a loadbearing element in timber structures shall be protected in such a way that they have at least the same fire resistance as the rest of the structure. In order that this degree of protection may be achieved, wood, chipboard or mineral wool etc of sufficient thickness may be used. Metallic materials in direct contact with the timber shall be insulated in such a way that their temperature does not exceed 300°C during the specified fire resistance period". There are proposals for the introduction of this structural regulation in Norwegian standards for calculation of the fire resistance of timber structures /6.20/.

6.19 and 6.21/. A fragmentary illustration of the results is given in FIG. 6.14 which shows the increase in fire resistance of bolted and nailed connections in shear owing to wooden cover sheets glued or nailed over the connection. /6.20/ gives the results of some preliminary studies, with thermal exposure according to ISO 834,concerning the possibility of increasing the fire resistance of timber connections by insulating the steel details with a fire retardant finish (3 coats of Unitherm) or a mortar (20 mm Pyrocrete 102).

Failure of splices, attachments and connections in the event of fire usually occurs due to large local deformations within the timber/steel contact area. This is verified in the few experimental investigations which have been published /6.21/ - /6.24/.

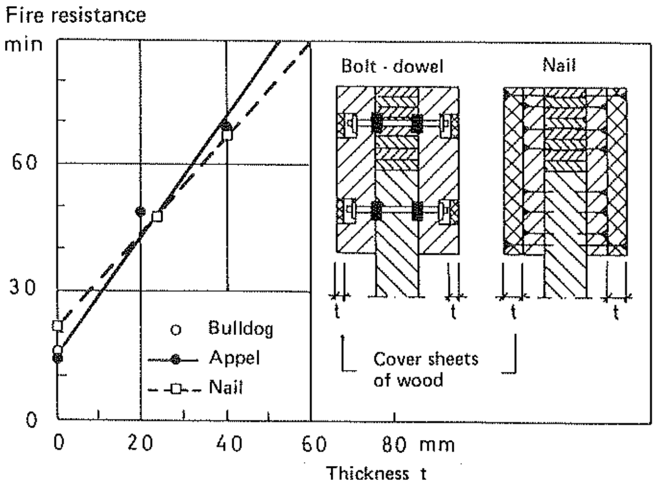


FIG. 6.14. Fire resistance of bolted and nailed connections in shear as a function of the thickness t of wooden cover sheets glued or nailed over the connection /6.14/.

There is no analytical model available which makes possible the calculation of the behaviour and loadbearing capacity of e.g. a nailed or bolted connection in the event of fire. On the other hand, models are in existence for similar conditions at ordinary room temperatures. These models are eminently suitable to form a phenomenological point of departure for the development of models which also cover fire conditions. Such a development would include the following components:

- A two or three dimensional model for calculation of the rate of charring, temperature gradient and moisture distribution for the wood around a heated nail or bolt.

erent charred layer, temperature and moisture conditions and for variable pin diameters, wood thicknesses and angles between the grain and the direction of force,

- similar experimental investigation for bolts in single and double shear for supplementary determination of the effect of friction in the connection,
- application - for variable thermal exposure - of the data obtained in these investigations to available models for the behaviour and loadbearing capacity of connections - see, for instance, /6.25/ in which a similar application is described for bolted connections in steel structures exposed to fire,
- experimental verification of the theory at model or full scale.

A research project of the structure described has a high degree of urgency. This also applies for a project of more limited character for the production of design data for determination of the required thickness of cover sheets and other types of insulation for bolted or nailed connections for real fire exposures, described, for instance, by the gas temperature-time curves according to FIG. 1.2.

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7. THE EFFECT OF FIRE RETARDANT ADDITIVES

7.1 Introduction

By means of flame retardants, the fire behaviour of timber structures during the different stages of a fire sequence - slow pyrolysis during the heating stage, ignition of the flammable gases formed, active pyrolysis and combustion with flaming, and smouldering, i.e. oxidation of the charcoal formed - can be altered in various respects. The mechanisms involved in the action of the flame retardants can be roughly broken down into mechanisms with a physical or chemical mode of action - FIG. 7.1 /7.1/. The effect of flame retardants of physical action includes energy absorption, release of non-flammable gases, and formation of diffusion resistant radiation protection layers on the surface of the material. For the chemical mechanisms, a distinction is made between action in the solid phase and action in the gaseous phase or flame.

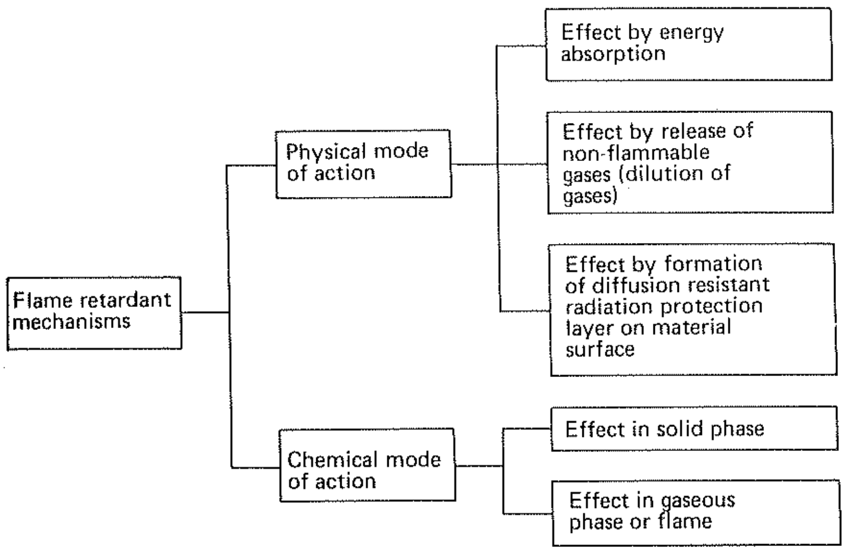

FIG. 7.1. Mechanisms of action of flame retardants.

In the case of many chemicals, the flame retardant effect is obtained by interaction between several physical mechanisms, or between physical and chemical mechanisms. The effect can be controlled by mixing the flame retardant chemicals, for instance in such a way that they complement one another during a complete fire sequence. The physical and chemical properties relevant to the differmelt, vapour pressure and latent heat of vaporisation, water solubility.

In the following, the effect of these mechanisms and their interrelationship is further developed according to a scheme presented in /7.2/.

7.2 Chemical mechanisms

In conjunction with action in the solid phase, the chemical flame retardant theory for wood and other cellulosic materials is based on a change of the rapid pyrolysis to a slow pyrolysis. If pyrolysis of cellulose could be steered towards the ideal complete dehydration into water and carbon, according to

$$(C_6H_{10}O_5)_n \rightarrow 6nC + 5nH_2O$$

then no flammable gases would be formed from the principal wood component until the temperature became high enough to initiate the water-gas reaction. Many flame retardants also steer decomposition in this direction. Even though the ideal reaction cannot be achieved, there is increased formation of charcoal, and the volatile components are richer in oxygen and thus have a lower heat of combustion. Formation of tar is also reduced. This has the effect that the initial stage involving slow pyrolysis is prolonged. According to the theory of chemical action in the solid phase, effective flame retardants prevent formation of laevoglucosane by blocking or removing the hydroxyl group on carbon atom No 6.

It is also possible during heating of lignocellulosic materials to bring about crosslinking of adjacent cellulose chains by elimination of water. The rate at which these crosslinks are formed is considerably affected by the presence of certain inorganic salts such as aluminium sulphate, ferric nitrate and copper nitrate.

In conjunction with action in the gas phase, flame retardants do not affect the formation of combustible products, but influence their later reactions. The flame retardant acts as an inhibitor in the chain reactions between free radicals in the flame by releasing gaseous products. This means that the protective effect is obtained mainly during the ignition phase and active pyrolysis, while the initial slow pyrolysis is unaffected. Flame retardants which modify the combustion process by means of this mechanism should have a high vapour pressure and be dissociated rapidly at the temperatures which prevail in the event of fire.

7.3 Physical mechanisms

(a) Absorption of energy

Energy absorption provides a flame retardant effect by virtue of the fact that the chemicals absorb large amounts of heat during heating. This can be achieved by giving the substance a high heat capacity or by making it subject to phase transitions or reactions which require large quantities of energy, such as fusion, sublimation, decomposition and dehydration. This mechanism exerts the greatest influence during the early slow pyrolysis.

(b) Dilution of gases

Many flame retardants decompose when heated and give off non-flammable gases such as water vapour, nitrogen or carbon dioxide. It is assumed that these gases protect the material in two ways. They both dilute the gas mixture and in this way render it non-flammable, and they shield the material from oxygen and in this way prevent combustion of this.

(c) Formation of protective layer

A flame retardant effect by the formation of a protective layer can be accomplished in three ways. One way is to spray or brush onto the surface a film which excludes oxygen from the surface of the material and prevents the escape of flammable gases. Such a layer must be very elastic, otherwise it is rapidly destroyed in the event of fire. Another way is melting of the added chemical and consequent formation of a film on the surface of the material. The protective effect is obtained in this case by reflection of heat, thermal insulation, exclusion of atmospheric oxygen, and prevention of the escape of flammable gases. Finally, protection can be obtained by the provision of a layer which intumesces under the action of heat to form a porous, thermally insulating coat similar to charcoal.

7.4 Interaction between different mechanisms

The flame retardant effect of many chemicals is due to interaction between several physical mechanisms or between physical and chemical mechanisms. A flame retardant chemical may have the following mode of action.

releases an inert gas and also forms an acid residue which has an action in the solid phase. The inert gas may have the dual function of diluting the gas mixture and of forming bubbles in the surface layer, thus increasing its thermal insulation capacity. Energy is also consumed during fusion and the decomposition reaction. In this instance interaction occurs between five different mechanisms /7.1/.

7.5 Different types of flame retardant

The technique of protecting wood by means of flame retardant additives has been used for a long time. Lyons /7.3/ states that reference to flame retardants extend over more than 200 years. The earliest reference to a flame retardant for wood in Chemical Abstracts is found in Volume 1 from 1905, and concerns a mixture of ammonium phosphate and boric acid, a preparation still often used at present. At about the same time there is discussion of sodium silicate, tungsten, borates and aluminium hydroxide, and chlorides of calcium, magnesium, zinc and tin. A British Patent dating from 1912 specifies as flame retardant a mixture of zinc, mercury and copper salts which are applied to the timber by subjecting it to a vacuum prior to impregnation. In 1914 the American Wood Preservers Association recommends NH_4Cl, $(NH_4)_2SO_4$ and NH_4 phosphates as particularly suitable preparations, and a publication of the same Association in 1944 quotes $Na_2Cr_2O_7$, $(NH_4)_2HPO_4$, $NH_2H_2PO_4$, $Na_2B_4O_7$, H_3BO_3, $ZnCl_2$, and chromated $ZnCl_2$, as suitable agents. References /7.2, 7.3/ tabulate a large number of flame retardants and associated methods of application.

Table 7.1 lists some flame retardants in common commercial use at present and their recommended chemical compositions.

Sellman et at /7.1/ has collated physical and thermal data for some inorganic flame retardant chemicals, broken down into borates, phosphates and silicates. The following conclusions can be drawn from this:

- In the case of borates the flame retardant effect is considered to be due to a combination of chemical action in the solid phase, energy absorption, development of diluent gases, and formation of a protective film on the surface of the material.

- In the case of ammonium phosphates, chemical action in the solid phase dominates, but release of diluent gases and energy absorption should provide additive effects.

- In the case of sodium silicates, the protective mechanisms are more difficult to evaluate, but the protective film formation mechanism is probably the dominant one.

- The modes of action of the different groups are similar, and they act at about the same stage of the fire sequence. Combinations of these are therefore not likely to produce an appreciable increase in flame retardant effect.

Table 7.1 (according to /7.3/)

Chemicals	Proportion	Specification
$(NH_4)_2SO_4$	78	Type 1[a]
$NH_4H_2PO_4$ or $(NH_4)_2HPO_4$	19	
$(NH_4)_2SO_4$	60	
H_3BO_3	20	
$(NH_4)_2HPO_4$	10	Type 2
$Na_2B_4O_7$	10	Minalith
$Na_2B_4O_7$	60	Type 3
H_3BO_3	40	
$ZnCl_2$	77.5	Type 4
$Na_2Cr_2O_7.2H_2O$	17.5	CZC
$ZnCl_2$	62	
$Na_2Cr_2O_7.2H_2O$	15.5	Type 4
$(NH_4)_2SO_4$	10	CZC(FR)
H_3BO_3	10	
$Na_2B_4O_7$	67-70	
$NH_4H_2PO_4$	33-30	
$ZnCl_2$	54	
$NH_4H_2PO_4$	46	
$ZnCl_2$	35	
$(NH_4)_2SO_4$	35	Protexol Class D
H_3BO_3	25	Pyresote
$Na_2Cr_2O_7.2H_2O$	5	

7.6 Conclusions

In relation to the behaviour and design for fire exposure conditions of loadbearing and separating constructions of timber, the above description of the effect of fire retardant additives points to the following research projects:

(1) A review of the existing state of knowledge and further analysis of the physical and chemical mechanisms involved in the action of flame retardants, and study of the possibilities of achieving an optimum interaction between different mechanisms at the different stages of a fire - slow pyrolysis during the heating phase, ignition of the flammable gases formed, active pyrolysis and combustion with a flame, and smouldering. In conjunction with certain applications, e.g. calculation of the rate of charring, it should be possible to study by means of analytical pyrolysis models the effect of fire retardants which are based on physical action in the solid state.

(2) A review of the existing state of knowledge and preparation of a detailed programme for further research concerning the effect of flame retardant additives on phenomena and properties which are critical in fire design of loadbearing and separating timber constructions - rate of charring, thermal properties, mechanical properties, the behaviour of splices and connections /7.4/ - /7.11/.

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8. SUMMARY OF THE PROPOSED PROJECTS. PRIORITIES

In the final section of each of the previous chapters, conclusions have been drawn concerning research projects of urgent necessity on the basis of the review of existing knowledge presented in that chapter. Research projects of an overriding character are described in Section 1.6. This section also lists a number of projects which relate to narrower subject areas. These projects are directly related to the different stages of fire design of loadbearing and separating timber constructions. The projects are described in greater detail in Sections 2.5, 3.5, 4.5, 5.3, 6.1.5, 6.2, 6.3 and 7.6 in the order in which they are encountered in the course of design.

In the following, brief descriptions are given of these projects, accompanied by an estimate of the staff requirement and the overall financial commitment. The estimate of the financial requirement has been based on the representative costs of university research. A description is first given of the projects which have a direct relation to the stages of the design process and are thus more limited in scope (Section 8.1), and the projects of more overriding character which concern the entire design process are then described (Section 8.2). In Section 8.3, finally, the interrelationship of the different projects is illustrated, and an overall strategic plan is given with regard to the necessary research effort.

8.1 Projects associated with the different stages of the design process

A Development of a simplified model for translation of the relationship between radiation level and the time to ignition into an ignition criterion for a temporally variable fire environment (Section 2.5).

Existing relationships between radiation and time to ignition have been determined experimentally or analytically for different materials and material combinations on the assumption of radiation levels constant in time. FIG. 2.3 gives examples of these relationships. In real fires, a material or material combination is subject to radiation exposure which varies in time. It is therefore of urgent necessity to develop a simplified model and an associated ignition criterion in order that real fire exposure and constant radiation level-ignition time curves may be interrelated, enabling a prediction to be

This is a combined experimental and theoretical project which requires access to equipment incorporating a radiant panel. The staff requirement is 1 researcher and assistants for about six months. Financial commitment: SEK. 250,000.

B Expansion of knowledge regarding the thermal properties of charred and uncharred wood (Section 3.5).

Such expansion of knowledge is needed in order to enhance the possibility of analytically calculating the rate of charring and the temperature and moisture distributions in the uncharred portions of timber structures exposed to fire. Attention should be primarily focused on thermal conductivity and specific heat capacity of both charred and uncharred wood at temperatures above 100°C.

The task comprises both critical appraisal of information in the literature and additional experimental determinations. Access is needed to equipment for determination of the thermal conductivity and specific heat capacity at varying moisture ratios and varying elevated temperatures, up to about 300°C for uncharred wood and up to about 500°C for charred wood. The staff requirement is approximately 1 researcher and assistants for about six months. Financial commitment: SEK. 300,000.

C Further work on existing relationships for calculation of the heat of reaction of wood in real fire conditions (Section 3.5).

Calculation of the heat of reaction of wood on the basis of data concerning enthalpy rise and phase transition energy is an important component of a mathematical model for analytical determination of the rate of charring and the temperature, moisture and density-time fields for a timber structure subject to variable fire exposure.

The task is predominantly a theoretical one, but must also comprise experimental verification studies at laboratory scale. Staff requirement is 1 theoretician and 1 experimentalist and assistants for about nine months. Financial commitment: SEK. 400,000.

D Development of a simplified model for calculation of the rate of charring and temperature distribution in thin-walled timber structures exposed to fire (Sections 4.5 and 6.2).

The rate of charring in a timber structure exposed to fire is governed partly by reaction kinetic protimber structures the rate of charring is mainly governed by the transport processes.

Existing models for calculation of the rate of charring have been developed for solid timber structures and therefore they are not applicable for thin-walled timber structures. A combined theoretical and experimental research project which will produce data for prediction of the depth of penetration of fire for thin panels of wood and wood-based materials under the action of different thermal processes is therefore of urgent necessity. It is expected that the experimental studies will be extensive.

Information provided by Project C is a component of the theoretical part of this research task. Coordination or integration of Projects C and D is therefore essential. Staff requirement for Project D - exclusive of the extraction of necessary information from Project C - is 1 theoretician and 1 experimentalist, and assistants, for about 1 year. Financial commitment: SEK. 700,000.

For an initial investigation associated with the above project, the Swedish Forest Products Research Laboratory has been allocated SEK. 100,000 by BRANDFORSK for the period 1982-84.

E Further work on a simplified model for calculation of the rate of charring, temperature and moisture distribution in fire-exposed timber structures of solid section (Section 4.5).

A simplified analytical model for determination of the depth of charring in solid timber structures subjected to variable thermal exposure is presented in /4.5, 6.9/ - see Subsection 6.1.1. This model can be used for calculation of a systematic basis for practical design of loadbearing structures in relation to a real fire exposure. The model has been developed for the one-dimensional case, assumes dry wood, and provides no information concerning temperature and moisture distribution in the uncharred portion of the structure. Reference /4.4/ presents an alternative one-dimensional model which also includes description of the temperature distribution in the uncharred portion of the cross section. References /4.1, 6.11/ describe a more general one-dimensional model for the pyrolysis of wood which, in addition to calculation of the rate of charring, also gives a method for approximate determination of the temperature and moisture condition in the timber structure. Further development, particularly with respect to the effect of moisture, is however needed in order that the method may be capable of easy practical application.

For the effect of moisture, development work may alternatively be associated with the following aspiration levels:

(a) Moisture transfer is ignored, and initial moisture and that produced during pyrolysis is vaporised at the original point in the cross section.

(b) A partial model for moisture transfer is included.

It is further important that existing and developed models should be extended so as to be valid for two and possibly three dimensional cases for practical application to beams and to different types of splices and connections (Section 6.3). The anisotropic properties of wood must be taken into consideration.

The results yielded by Projects B and C constitute the initial information for the above project which is principally theoretical in nature. However, integration of a simplified model for moisture transfer requires experimental determination of a number of material constants. In addition, some verification tests are required for the overall model.

The staff requirement for Project E - exclusive of the extraction of the necessary information from Projects B and C - is 1 theoretician and 1 experimentalist, and assistants, for about 1 year. Financial commitment: SEK. 500,000.

F Development of an analytical material model for the stress-strain behaviour of wood in conjunction with transient stress, temperature and moisture states (Section 5.3).

For practical calculation in timber structures exposed to fire of the deformations, instability loads and induced forces and moments due to restraint on deformations, it is necessary to have access to an experimentally verified material model of the mechanical behaviour of wood in conjunction with simultaneous transient stress, temperature and moisture states. Development of such a model is therefore an urgent necessity.

Experimentally, such a project comprises both investigations on small specimens and supplementary tests on structural elements of ordinary dimensions. A natural arrangement of a small scale investigation would be:

(a) Rapid loading tests at stable temperatures and variable initial moisture ratios for determination of the complete stress-strain curve.

(c) heating tests to failure at stable load and variable initial moisture ratio,

(d) measurement of the moisture ratio for the same types of specimen as in (a) - (c) for unloaded specimens under variable heating.

Parallel tests on sealed specimens may have to be included.

Staff requirement for the project is 1 researcher and assistants for about 2 years. Financial commitment:SEK. 500,000.

For a project of the above type, the Swedish Board for Technical Development STU has allocated SEK. 413,000 to the Division of Building Fire Safety and Technology, Lund Institute of Technology. Work on the project is in progress. Further, the Swedish Forest Products Research Laboratory has previously been granted SEK. 118,000 by STU for experimental production, by means of small specimens of 5-10 mm^2 cross section, of data concerning the mechanical properties of wood at high temperatures and variable moiture ratios. A report on this investigation is under preparation.

G Experimental and theoretical study of the effect of biological and chemical structure on the mechanical properties of wood under different temperature and moisture conditions (Section 5.3).

No investigations have been published as to why temperature and moisture affect the mechanical properties of wood, only the way in which these are changed A project which elucidates whether the biological differences between different species of timber or within the same species can explain phenomenologically some of the large scatter in test results relating to the mechanical properties of wood for different combinations of temperature and moisture conditions is therefore of urgent necessity /5.1/. Such a project should also comprise a simplified analytical model which takes into consideration the growth ring structure of wood and the relationship between cellulose and lignin.

The staff requirement for this project is 1 wood chemist and 1 materials engineer, and assistants, for about 1 year. Financial commitment: SEK. 500,000.

H Further development of analytical methods and computer programs for calculation of the behaviour and limit states of timber structures of solid section in the event of fire (Subsection 6.1.5).

on simplified assumptions regarding all the components of the method. Applicability of these methods is thereby confined to approximate calculations of ultimate limit states and critical loads for certain types of instability phenomena. The methods do not permit calculation of the deformations of the fire-exposed timber structures, nor calculation of the induced forces and moments due to restraint on deformation.

Access to a more advanced model for calculation of the rate of charring, temperature gradient and moisture distribution according to Project E, and an analytical material model for the mechanical behaviour of wood in conjunction with transient stress, temperature and moisture states according to Project F, is essential in order that existing design methods for fire-exposed timber structures of solid section may be brought into an advanced state of improvement and expanded as regards fields of application.

Such work incorporates development of numerical methods based on finite elements or finite differences, and associated computer programs, for the fire behaviour and limit states of different types of structure. The failure modes of interest are bending, shearing, torsion, buckling and lateral torsional buckling.

A project of this content is predominantly theoretical in nature. Verification tests at full or reduced scale must be added. Staff requirement is 1 researcher and assistants for about 2 years. Financial commitment: SEK. 600,000.

I Development of analytical and numerical methods and computer programs for calculation of the behaviour and limit states of lightweight and composite timber structures under fire exposure conditions (Section 6.2).

All the information concerning the behaviour and limit states of lightweight and composite structures under fire exposure conditions, with regard to their loadbearing and/or separating function, has been obtained from standard fire tests under thermal exposure according to ISO 834. No analytical methods have been published as yet regarding the design of these types of timber structure.

Research work which may result in the development of such analytical methods is therefore of great urgency. This applies both for thermal exposure according to ISO 834 and for real fire exposure. A simplified model for calculation of the depth of combustion for thin panels of wood and wood based materials subject to different types of thermal exmethods. The analytical methods must be verified by experimental investigations at full or reduced scale.

A project which has the object outlined above can be tackled on the basis of two alternative aspiration levels:

(a) Design is confined to limit states for certain simple types of structure,

(b) design is extended so as to comprise deformations and forces and moments induced due to restraint on deformation, application being of a more general character with respect to the type of structure.

A project based on the higher aspiration level includes development of numerical methods on the basis of finite elements or finite differences, and associated computer programs, for the fire behaviour of different types of structure. Access to a material model for the mechanical behaviour of wood at transient stress, temperature and moisture states according to Project F is therefore essential.

For aspiration level (a) the staff requirement - exclusive of Project D - is 1 researcher and assistants for about 1 year. Financial commitment: SEK 350,000.

For aspiration level (b) the requirement - exclusive of Projects D and F - is 1 researcher and assistants for about 2 years. Financial commitment: SEK. 600,000.

J Development of analytical models for calculation of the behaviour of splices, attachments and connections, and their loadbearing capacity, under fire exposure conditions (Section 6.3).

A research project made up of two parts appears to be of urgent necessity in this respect.

The first part comprises production of design data for determination of the required thickness of cover sheets and other types of insulation for bolted and nailed connections under real fire exposure conditions. In conjunction with cover sheets of wood or wood-based materials, the results provided by Project D constitute essential input information.

The second part comprises development of an analytical model for calculation of the behaviour and loadbearing capacity under fire exposure conditions of e.g. a bolted or nailed connection, and experimental verification of this at full or reduced scale.

Staff requirement for the project is 1 researcher and assistants for about 18 months. Financial commitment: SEK. 600,000.

Funds amounting to SEK. 155,000 have been allocated to the Technical Department of the Swedish Fire Protection Association by BRANDFORSK and the firm of Svenskt Limträ AB for an investigation relating to the second part of this project.

K A review of the existing state of knowledge and preparation of a detailed research programme concerning the effect of fire retardants on phenomena and properties which are critical with regard to fire design of loadbearing and separating timber constructions (Section 7.6).

Examples of such critical phenomena and properties are ignition, rate of charring, thermal properties, mechanical properties and the mode of action of splices and connections.

Staff requirement is 1 researcher for about six months. Financial commitment: SEK. 100,000.

L A review of the existing state of knowledge and further analysis of the physical and chemical mechanisms involved in the action of flame retardants, and a study of the possibilities of achieving optimum interaction between different mechanisms at the different stages of a fire (Section 7.6).

The project is a combination of experimental and theoretical work. Description of the background to the project is given in Sections 7.1 - 7.5.

Staff requirement is 1 theoretician and 1 experimentalist and assistants for about 18 months. Financial commitment: SEK. 800,000.

8.2 <u>Overriding projects which have a bearing on the entire research process</u>

A Development of a method for analytical determination of the fire resistance of elements of construction of timber (Sections 1.2 and 1.6).

Determination of the fire resistance of elements of construction is at present entirely dominated internationally by standard fire tests according to ISO 834. As an alternative, an increasing number of countries now permit determination of fire resist-

With regard to timber structures, the present state of knowledge permits such analytical determination of fire resistance with acceptable accuracy for solid timber structures such as beams and columns. On the other hand, analytical determination of fire resistance is not possible at present for light-weight and composite structures of loadbearing and/or separating function. The same also applies for all types of structure which contain splices, attachments and connections.

An overriding research project which has the object of providing data for more general utilisation of the possibility of analytically determining the fire resistance of elements of construction of timber comprises the component projects D, I and J described in Section 8.1. Apart from these projects, the overriding project also contains systematised calculation of design data and a special study of consistency problems in view of the differences in conditions which may occur when fire resistance is determined analytically and when it is obtained by standard tests.

One of the reasons why this project is of great importance is that it may provide greater opportunities for analytical fire classification in the place of classification based on the results of standard fire tests, which may in future produce appreciable savings in cost in conjunction with the development and marketing of new products and design solutions. In conjunction with increased international acceptance of analytical fire classification, this project may also be instrumental in facilitating the type approval procedure for Swedish timber products for export.

Staff requirement for the overriding project - apart from the requirement for the component projects D, I and J - is 1 researcher and assistants for about 1 year. Financial commitment: SEK. 300,000.

B Development of a method for fire design of loadbearing and separating elements of construction on the basis of real fire exposure (Sections 1.3 and 1.6).

Analytical design of loadbearing and separating elements of construction on the basis of real fire exposure is feasible at present for most types of steel structure and for certain types of concrete structure. In the course of 1983, a manual which will appreciably improve the practical design situation will probably be published for analytical design of concrete structures.

It is essential that knowledge of the behaviour and design of fire-exposed timber structures should be developed to a level equivalent to that for steel

An overriding research project for such a development comprises the component projects B, C, D, E, F, I and J described in Section 8.1 if practical application is to be universal. In addition to these component projects, the overriding project therefore includes as a primary task the production of a design manual. The staff requirement for this - exclusive of the staff required for the component projects - is 2 researchers and assistants for about 2 years. Financial commitment: SEK. 600,000.

C Production of data for determination of the equivalent fire duration for elements of construction of timber (Sections 1.4 and 1.6).

The concept of equivalent fire duration has been introduced to enable real fire exposure and thermal exposure according to standard fire tests (ISO 834) to be interrelated. Equivalence is defined with reference to the criterion that both types of exposure should, for the structure concerned, produce the same critical effect with respect to the relevant limit state.

Data are available at present for calculation of the equivalent fire duration for steel structures and reinforced concrete structures subject to certain types of failure. For other types of structure, including timber structures, the concept of equivalent fire duration is incomplete or has not been studied at all.

A project which has the object of producing data for determination of the equivalent fire duration for elements of construction of timber must be based on the results of the overriding projects A and B. On the basis of an international perspective, this project is of great urgency. Nationally, in view of the fire design philosophy adopted by Swedish Building Code, this project is of lower priority than the other overriding projects.

With the results of the overriding projects A and B as the points of departure, the staff requirement for the project concerning equivalent fire duration is 1 researcher and assistants for about 9 months. Financial commitment: SEK. 200,000.

D Further development of the design method according to the overriding project B so as to adapt this to modern loading and safety regulations (Sections 1.5 and 1.6).

Safety theory methods are being applied to an increasing extent internationally for the design of

In order that such development may be meaningful, the design method must be made up of functionally well defined and verified analytical models, the uncertainties and reliability levels of which can be defined. The design method described by means of the overriding project B meets this requirement.

A design method for structures exposed to fire, which is based on safety theory and in which the statistical influences are taken into consideration by means of characteristic values and partial safety factors for the quantities involved, would make possible a greater degree of economic optimisation. In principle, such a method would also eliminate the present differences in fire requirements and application limitations between structures of combustible and non-combustible materials.

Further development of the overriding project B as described above, so as to adapt this to modern loading and safety regulations, requires 1 researcher and assistants for about 2 years. Financial commitment: SEK. 600,000.

8.3 Interrelationship between the projects. Priorities.

The interrelationship between the projects described in Sections 8.1 and 8.2 is illustrated by the flow chart in FIG. 8.1. Projects associated with the different stages of the design process have been designated 8.1A, 8.1B, 8.1C etc, where A, B and C directly refer to the project designations in Section 8.1. Similarly, overriding projects which concern the entire design process have been designated 8.2A, 8.2B, 8.2C etc, where A, B and C directly refer to the project designations in Section 8.2.

Arrows drawn with full lines between projects denote a strong relationship, and arrows drawn with dashed lines a weaker relationship. Projects inside double frames have been assigned the highest priority, and projects inside single frames a lower priority - but without being of low priority. Projects 8.1K and 8.1L which deal with the effects of fire retardants, and their relationship with other projects, have been placed as a separate group in order to emphasise that, from the

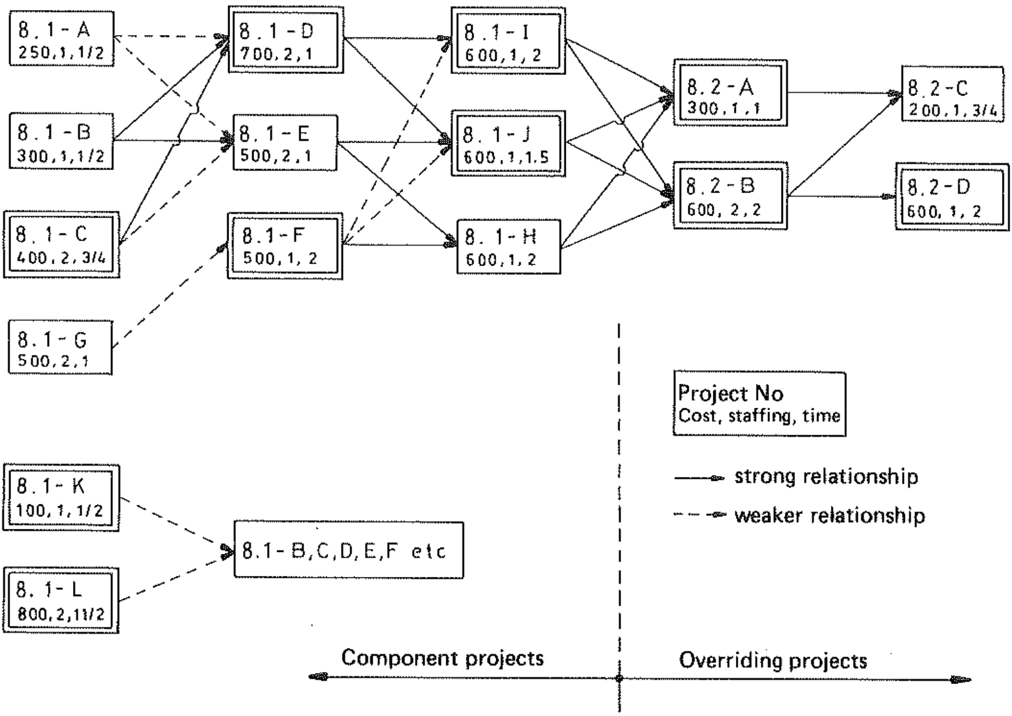

FIG. 8.1. Interrelationship of the research projects. Double frames denote projects of the highest priority, and single frames projects of lower priority.

Each frame specifies the project number, financial commitment in 1000 SEK, staff requirement and required project duration. The estimated overall cost of the whole package of projects is SEK. 7.55m, of which SEK. 5.85m is needed for the projects associated with the stages of the design process, and SEK. 1.7m for additional expenditure in respect of the overriding projects. The total cost of the projects of the highest priority which have been placed in double frames is SEK. 5.2m. To an absolutely dominant extent, all projects are of an applied character. Some projects (8.1C, D, E, F and G) contain elements of fundamental research character amounting, roughly, to about SEK. 500,000 in all.

The interrelationship between the different projects in the overall research programme, which is illustrated in the flow chart in FIG. 8.1, emphasises the urgent need for a national coordination of current and future research within this programme. Planning for such coordination comprises a review and assessment of the staff and equipment requirements for integrated overall commitment, including calculations of resources and time development and production of practical design data comprised in the overriding projects. This is exemplified in FIG. 8.2 with regard to the final goal 8.2-A in relation to lightweight and composite structures, and in FIG. 8.3 with regard to the final goal 8.2-D in relation to solid timber structures. The coordinated plan

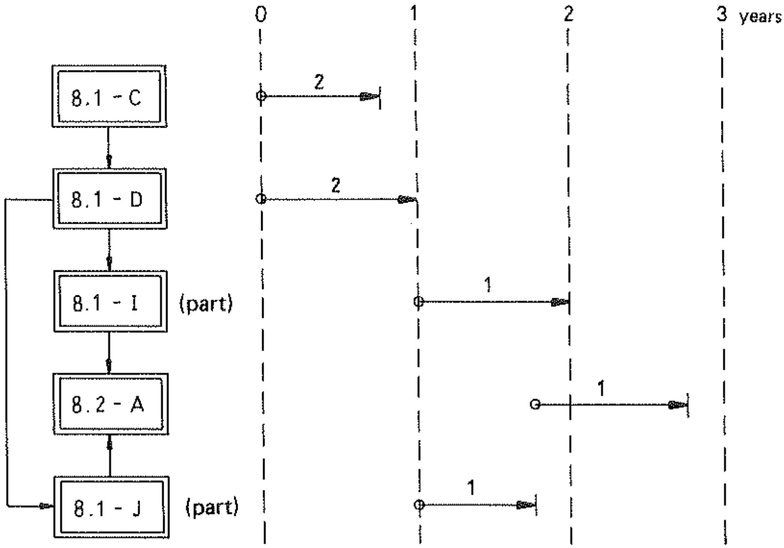

FIG. 8.2. Time and resource scheme for a nationally coordinated research effort for development of a method for analytical fire classification of lightweight and composite timber structures, adapted for practical application. The numbers above the arrows indicate the estimated number of researchers needed for each project.

for research should also include an investigation of the way in which other activity, primarily current and planned international research and development work, may provide support for the research programme. It is probable that a number of standard fire tests on newly developed elements of construction of timber will be carried out during the programme period. It is essential that these should be made use of for the information they may give to the research programme. An analysis of the supplementary measurements which are required for such information is therefore an urgent initial

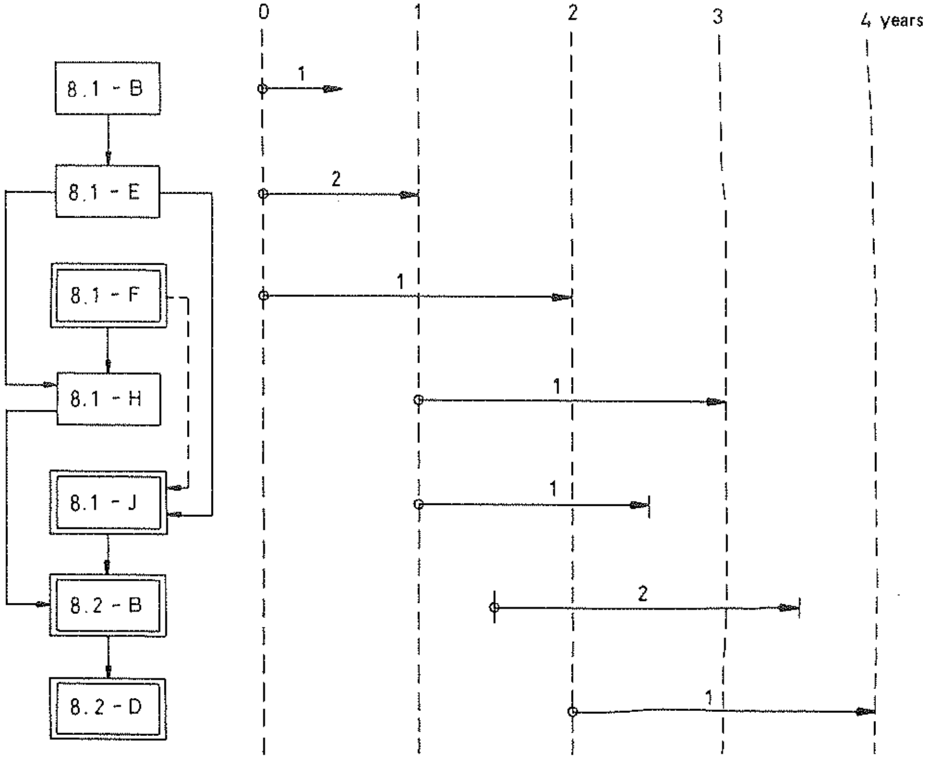

FIG. 8.3. Time and resource scheme for a nationally coordinated research effort for development of an analytical fire design method for solid timber structures, based on the characteristics of real fires and adapted to modern loading and safety regulations. The numbers above the arrows indicate the estimated number of researchers needed for each project.