9112080

I

RAPPORT

Jürgen König, Joakim Norén

Two Papers on Fire-exposed Load Bearing Wood Frame Members

Presented at the 1991 Timber Engineering Conference, London, and at Meeting 24 of CIB W18A – Timber Structures, Oxford, 1991

Trätek

INSTITUTET FÖR TRÄTEKNISK FORSKNING

Jürgen König, Joakim Norén

TWO PAPERS ON FIRE-EXPOSED LOAD BEARING WOOD FRAME MEMBERS
Presented at the 1991 Timber Engineering Conference, London,
and at Meeting 24 of CIB W18A - Timber Structures, Oxford, 1991

Trätek, Rapport I 9112080

ISSN 1102-1071
ISRN TRÄTEK-R--91/080--SE

Nyckelord

charring
fire resistance
load capacity
stiffness
test methods
wood failure

Stockholm november 1991

Rapporter från Trätek — Institutet för träteknisk forskning — är kompletta sammanställningar av forskningsresultat eller översikter, utvecklingar och studier. Publicerade rapporter betecknas med I eller P och numreras tillsammans med alla utgåvor från Trätek i löpande följd.

Citat tillåtes om källan anges.

Reports issued by the Swedish Institute for Wood Technology Research comprise complete accounts for research results, or summaries, surveys and studies. Published reports bear the designation I or P and are numbered in consecutive order together with all the other publications from the Institute.

Extracts from the text may be reproduced provided the source is acknowledged.

Trätek — Institutet för träteknisk forskning — betjänar de fem industrigrenarna sågverk, trämanufaktur (snickeri-, trähus-, möbel- och övrig träbearbetande industri), träfiberskivor, spånskivor och plywood. Ett avtal om forskning och utveckling mellan industrin och Nutek utgör grunden för verksamheten som utförs med egna, samverkande och externa resurser. Trätek har forskningsenheter, förutom i Stockholm, även i Jönköping och Skellefteå.

The Swedish Institute for Wood Technology Research serves the five branches of the industry: sawmills, manufacturing (joinery, wooden houses, furniture and other woodworking plants), fibre board, particle board and plywood. A research and development agreement between the industry and the Swedish National Board for Industrial and Technical Development forms the basis for the Institute's activities. The Institute utilises its own resources as well as those of its collaborators and other outside bodies. Apart from Stockholm, research units are also located in Jönköping and Skellefteå.

CONTENT

PREFACE

A comprehensive investigation into fire-exposed wood frame members under pure bending is in progress at the Swedish Institute of Wood Technology Research. Some of the results of the work were presented at two timber engineering conferences in 1991. Each of these two papers reflects a different state of the work, the first one at the beginning of the year, and the second one in August. While the first paper gives only some typical results in a very concentrated form, the second one contains complementary results and an approach on modelling this type of wooden members.

Compared with the original papers published in the conference proceedings, the lay-out of figures is slightly different due to changes in software, and some misprints have been corrected.

A complete research report will be published when the work is terminated, including the investigation of dimensions other than those dealt with in these two papers.

Stockholm, November 1991

FIRE TESTS ON TIMBER FRAME MEMBERS UNDER PURE BENDING

J König* and J Norén*

Timber frame members in pure bending were exposed to fire on one side in a small furnace. The specimens were made of the member itself and surrounding materials such as boards and rock wool insulation, representing typical thermal conditions in floors and exterior walls. Relationships between bending load capacity and time to failure were established. The flexural stiffness and the location of the centre of gravity were determined. Strength and stiffness were influenced by the load direction, and, when the fire exposed side was in compression, also by the load level.

BACKGROUND AND SCOPE

Our knowledge of the properties of fire-exposed light wood members as they are used in timber frame structures as wall studs and floor joists is still limited, especially when the members are surrounded by other building materials such as mineral wool and boards. Most investigations have concentrated on large sections. In small members conditions are more complicated. Thus simplified methods which are used in heavy-timber fire design can not be assumed to be valid in small members. For example it is not known to what extent strength and stiffness is influenced by transient states of temperature and moisture content in the wood.

In order to avoid these problems the investigation described in this paper has been started. Two typical types of structures exposed to fire on one side are considered. In load-bearing external walls the stud will, due to increasing eccentricity of the load, deflect towards the exterior cold side of the stud. The stud acts as a beam column with a large bending moment which causes compressive stresses on the hot side of the stud. See e.g. König /1/. In floors the joists are in bending and their hot side is in tension. The sides of the wood members are usually protected by mineral wool.

The main goal was to make it possible to develop a simple model which can be used in the design of typical applications in timber frame structures as walls and floors. Secondly the results should be used to verify more sophisticated analytical models to be developed in the future. In this paper only a description of phenomena will be given. The work is still going on and therefore

* Research Scientists, Swedish Inst. for Wood Technology Research

only some preliminary results can be presented here. It is planned to discuss different approaches to modelling the effective cross section in another paper /2/.

Until now in fire tests the loading has normally been put equal to design load without making a more precise prediction of load capacity of the specimen. In many applications design load in hot design is different from design load in cold design. The designer is interested in knowing the load capacity of a member after a specific fire resistance rating required in the building regulations. One of the goals was therefore to establish a relationship between fire resistance and load capacity and, since stiffness is essential in failure due to column buckling, to determine also the decrease of stiffness and change of the location of the centre of gravity of the residual section during the tests.

In walls the load acts in axial direction and the failure mode is buckling of the stud. The failure load of axially loaded wood members is very sensitive to imperfections which are inevitable due to the inhomogeneity of wood. In tests scatter would therefore normally be large and have an influence on the accuracy of the results. Tests are thus made only in bending, in the expectation that the mechanical properties obtained from bending tests could be used in calculations of axially loaded wall studs, e.g. by using the analytical model presented in /2/.

EXPERIMENTS

Material

The wood members were fairly free from knots. In an investigation Norén /3/ has shown that in fire exposure the influence of knots on the reduction of load bearing capacity could be disregarded. In the first part of this investigation specimens with the dimensions 45x145 mm^2 were studied. Further dimensions to be tested will be 45x95 and 45x195 mm^2. All specimens were of spruce (picea abies). All specimens were conditionned at 20°C and 65% RH. The resulting moisture content was about 14%. The range of density, i.e. oven-dry mass per volume of the wood at actual moisture content, was between 323 and 471 kg/m^3, and its average value was 416 kg/m^3.

The insulation material used was rock wool with a density of 30 kg/m^3 and a thermal conductivity of λ=0.040 W/m°C. Gypsum plasterboard (wallboard) was used with a thickness of 12.5 mm and a weight of 9 kg/m^2. The boards were attached to the wood member using self-drilling screws with a length of 38 mm and a diameter of 3.8 mm. All these data are nominal.

Reference tests at normal temperature

A sample of 12 pieces was chosen to be tested to failure in edgewise bending in a four-point ramp load bending test according to ISO 8375. In the tests the specimens were placed in the testing machine so that knots which could influence the failure load were located on the compression side of the beam. A regression analysis was made showing that the results could be desribed by correlation between bending strength and density, and that the contribution of flexural stiffness could be disregarded. Thus the expression

$$f_m = 0.1376\, r_{0u} \tag{1}$$

was used to predict bending strength f_m at normal temperature of the specimens to be used in fire tests. See Figure 1. The coefficient of correlation was determined as $r^2=0.42$.

Testing equipment and specimens in fire tests

Since the test specimens should represent the thermal conditions in an insulated timber frame wall, the test specimens of series 1 and 3 consisted of the wood member, mineral wool protecting its sides from fire, and attached strips of gypsum plasterboard on the cold side, and, in series 2, in addition a whole piece of plasterboard attached to the fire exposed side of the beam. See Figure 2. The area of the wall exposed to fire was 0.6 m x 1.0 m, the width 0.6 m representing the distance between the wall studs. By using strips of board on the cold side, composite action was eliminated. In practical applications composite action can easily be added in the analytical model, allowing for taking into account a wide variety of boards and ways of attaching these to the wood member. The mineral wool blocks were tied against the beam and suspended from the plasterboard strips attached to the upper side using 4 mm thick steel wires and plates.

A small gas-fired furnace was used in the fire tests. Its interior length was 1 m, and its width and depth were 0.6 m. The specimen was placed on two supports outside the furnace, forming a cover to the furnace. See Figure 2. The sides of the specimen above the walls of the furnace were protected by removeable insulated frames. The load was applied at the ends of the member by means of hydraulic jacks with reversible load directions.

In order to determine the position of the neutral axis of the member during the different stages of the tests, the deflection and strain of the cold side of the member was recorded over the gauge length of 900 mm by means of a device which was attached to the wood member. See Figure 3. Temperature was measured in the wood members but these data are not presented in this paper.

Fire tests

Series No. 1 - Fire-exposed side in compression. This series contains 12 specimens. Different loads were applied in the range of 10 to 77% of predicted load capacity at normal temperature. After application of the load, the fire exposure was started and the temperature increased following the standard fire curve according to ISO 834. The load was held constant until failure occured. After failure the gas burner was immediately turned off, the specimen removed and the fire in the member was extinguished with water.

From each member five approximately 10 mm thick slices were cut out, the charcoal was removed and the piece was put back into the climate chamber in order to be re-conditioned. Then the charring lines were recorded using a digitizer. Typical plots are shown in Figure 3, representing the residual section at failure at relative

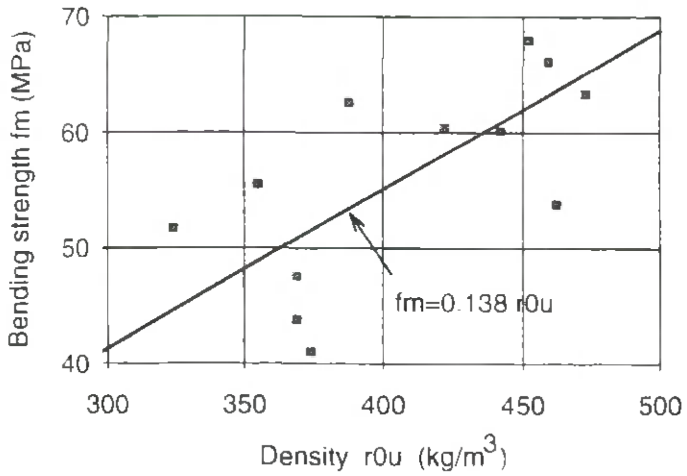


Figure 1 Bending strength versus density in reference test series.

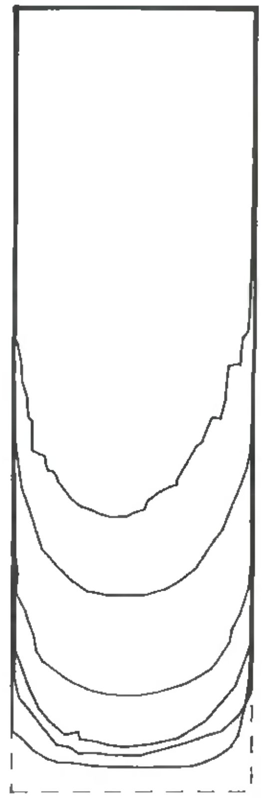


Figure 3 Recorded charring lines at different times to failure.

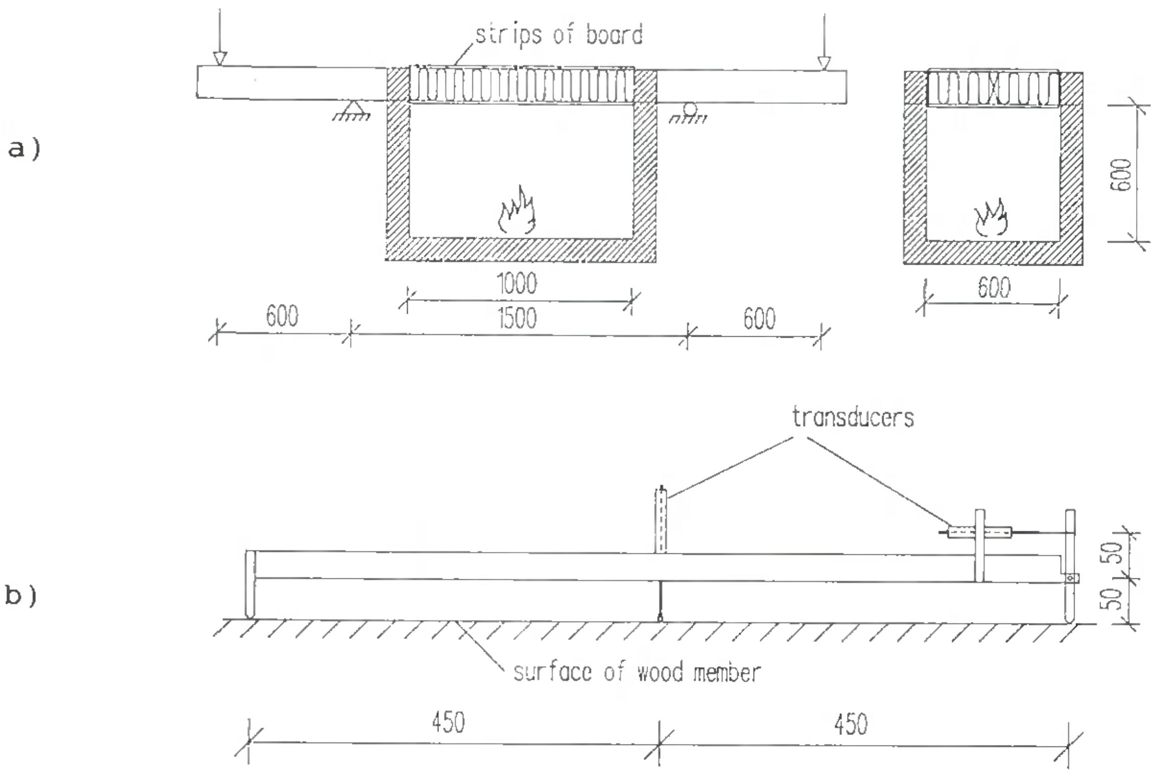


Figure 2 a) Testing equipment and specimen. b) Principle of device for measuring deflection and strain on the upper side.

load levels of 10, 15, 30, 49, 59 and 77%.

Series No. 3 - Fire-exposed side in tension. The 15 specimens of this series were loaded at relative load levels in the range between 10 and 70%. The testing procedure was the same as above.

Results - Comparison of test series Nos 1 and 3. The test results are shown in Figures 4 and 5. In Figures 4a and 5a the relationship of the relative load M_f/M_0 versus time to failure is shown. For each specimen two different time values are plotted. The measured test value is marked by a square. Since a proportionality exists between the charring rate and the inverse value of density, standardized time-to-failure values were calculated with respect to the average density in each series. These standardized values are marked as triangles in the diagram.

For both series of time values, regression curves were determined using an exponential function with intercept equal to unity. The expressions given in the figures refer to the recorded test values. The expressions for standardized time values are almost the same. The coefficient of correlation r^2 is 0.990 and 0.977 for series 1 and 0.864 and 0.845 respectively for series 3. These results show that the scatter of strength is low at elevated temperatures. The scatter is greater in series 3 when the fire-exposed side of the member is in tension due to some influence from minor knots in the beam. Some specimens failed without reaching large deflections. Generally the deflections are smaller in series 3. The coefficients of correlation are slightly lower when standardized time values are used, but the difference is negligible.

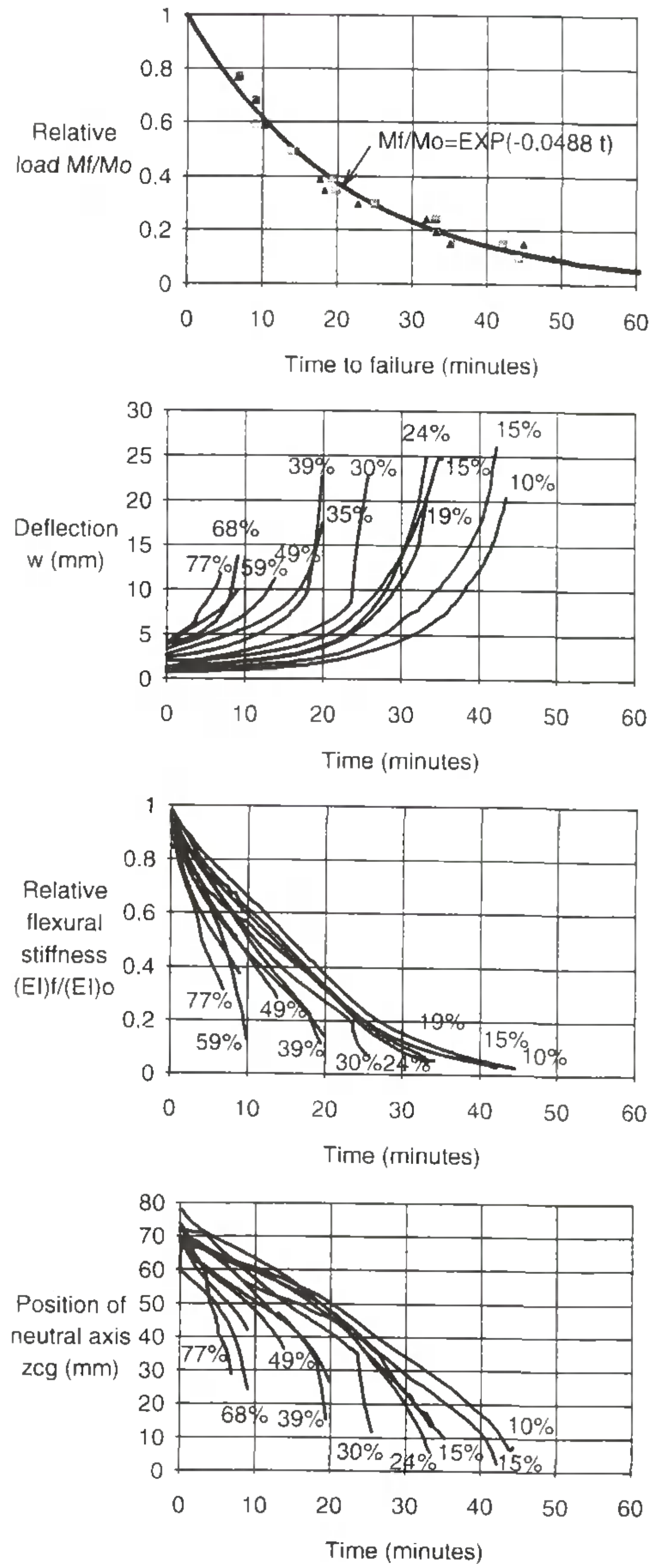
The magnitude of flexural stiffness in relation to its initial value at cold state is shown in Figures 4c and 5c. The flexural stiffness was calculated assuming a constant curvature within the gauge length. In series 1 the rate of decrease of stiffness is dependant on the relative load level. High loading from the beginning results in large plastic deformations due to buckling failure of the grain of the wood on the compression side of the member. This effect is increased by the elevated temperature. For specimens with relative-load levels below about 30% the rate of stiffness reduction is not influenced by the loading. In series 3 there is no influence of load level on stiffness-decrease rate.

Plots of the position of the neutral axis are presented in Figures 4d and 5d as its mean distance from the upper unexposed edge of the member within the gauge length L_g. These curves are calculated using the recorded strain values u/L_g and deflections w. Assuming that strain varies linearly across the depth of the section, it can be shown that

$$z_{cg} = -\frac{L_g}{8w}\left[u - L_g + \frac{L_g^2}{4w}\arcsin\frac{4w}{L_g}\right] \tag{2}$$

The last two terms, which are put in brackets, take into account the shortening of the beam due to deflection. There is a considerable influence of type of loading, and, in series 1, of the load level. When the fire-exposed side is in compression, the

a)
b)
c)
d)



<u>Figure 4</u> Test results of series 1 - Fire-exposed side in compression.

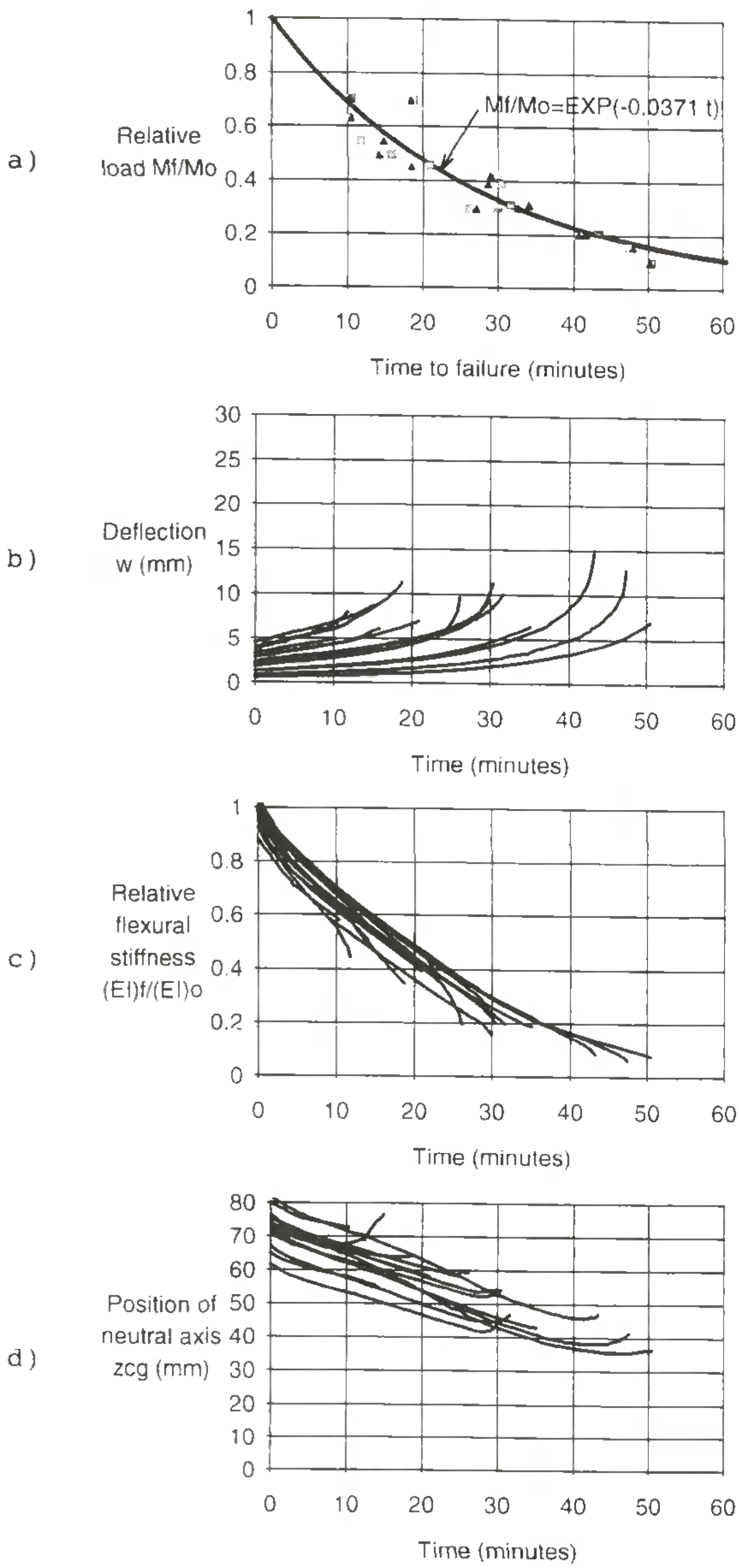


Figure 5 Test results of series 3 - Fire-exposed side in tension.

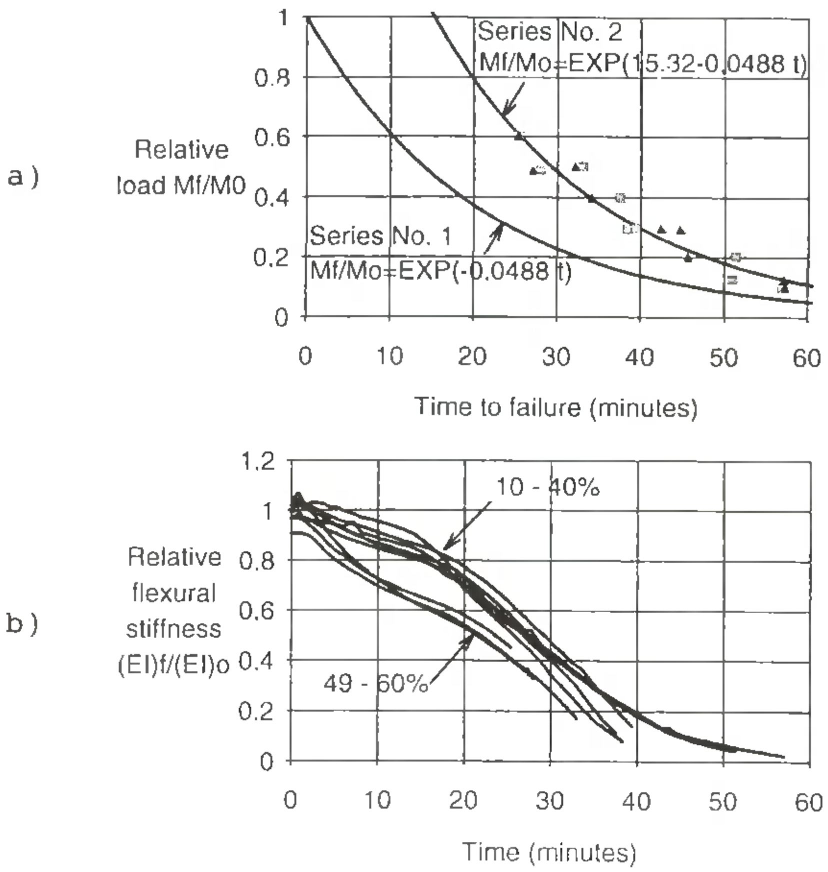


Figure 6 Test results of series 2 in comparison with series 1 - Effect of protection by 12 mm gypsum plasterboard.

displacement of the centre of gravity is much greater than in beams with this side in tension.

Series No. 2 - Fire-exposed side in compression and gypsum plasterboard attached to the member. The testing procedure of this series of 9 specimens was the same as above, with the exception that the flexural stiffness was also determined before attaching the board. The results are presented in Figure 6. A regression analysis for the relationship of relative load capacity versus time to failure was performed using the same shape of exponential function as had been obtained from the analysis in series 1. The coefficient of correlation is 0.927 and the difference in time to failure is 15.4 minutes. About the same difference of time is valid concerning decrease of stiffness, cf. Figures 6b and 4c.

REFERENCES

/1/ König, J., The structural behaviour of axially loaded wood studs exposed to fire on one side, Swedish Inst. for Wood Techn. Res., No. I 8808057, Stockholm 1988

/2/ König, J., Modelling the effective cross section of timber frame members exposed to fire. (Tentative title of planned paper). CIB-W18A Meeting Twenty-four, Oxford 1991

/3/ Norén, J., Failure of structural timber when exposed to fire, Int. Conf. on Timber Engineering, Seattle 1988

MODELLING THE EFFECTIVE CROSS SECTION OF TIMBER FRAME MEMBERS EXPOSED TO FIRE.

by J. König

Swedish Institute for Wood Technology Research

ABSTRACT

The results from fire tests on light, partly protected timber frame members under pure bending are used in order to model the effective cross section of this type of structural members. Since the test results made it possible to regard the influence of some parameters as the influence of the load level in relation to load capacity at normal temperature, the state of stresses, the loading rate and density, the modelling of structural timber in fire is dicussed in a wider perspective and some of the consequences for the requirements of an analytical model are described.

INTRODUCTION

Structural timber exposed to fire performs in a predictable manner. The charring layer increases in depth at an approximately constant rate and the residual section of the member is able to maintain a considerable load-bearing capacity under long time. Due to this behaviour heavy timber is a well-reputed structural material with respect to fire loading. Heavy timber structures do not normally need to be protected as is in the case of steel structures.

Most of the research into the load-bearing capacity of timber members in fire has been done in the field of heavy timber structures, i.e. normally glued laminated timber /1/, /2/. In the tests specimens were chosen fulfilling the requirements of a special quality class according to the national building code and the load was put equal to the "allowable load" according to the code or a part thereof. Since the real load-bearing capacity of the specimen was unknown - at the time of the tests there existed no reliable non-destructive method of predicting strength of heavy timber members - the resultant fire resistance ratings obtained from the fire tests were related to the design load given in the code and not in relation to the load-bearing capacity at normal temperature.

Charring rates which are applied in different building codes, vary considerably. In most cases they are in the range between 0.5 and 1.0 mm/min. There are various reasons for this. Since the material close to the char-layer is strongly affected by elevated temperature, the decrease of strength and modulus of elasticity is regarded either by applying a notional charring rate which is higher than the real one, or by assuming that strength and modulus of elasicity of the uncharred residual section is reduced. Another reason should be that the charring rates are calibrated to a, rather arbitrary, load level whose relation to load capacity at normal temperature is not known. The introduction of strength classes in codes for timber structures, i.e. the material is characterized by its characteristic strength, makes it necessary to determine charring rates which are related to the real decrease of load-bearing capacities of the members.

In the work on Eurocode 5 - Timber Structures - structural fire design is an essential part. A first draft on structural fire design of timber structures has been presented in 1990 /3/. Within CEN TC250/SC 5 a project team has been appointed with the task of redrafting the first version, taking into account the national comments which have been made.

One of the tasks is to agree on charring rates to be adopted in the code. It has to be decided whether strength and stiffness of the residual section has to be regarded as reduced or unreduced in relation to its values at normal temperature. The aim of this paper is to contribute to the discussion on modelling the effective section of timber members and on determining the relevant parameters.

FIRE TESTS

Some of the problems in modelling can be elucidated by referring to the results from an experimental investigation which is in progress at the Swedish Institute for Wood Technology Research. Some of the results are presented in /4/. Even though the thermal conditions differ from the general case of unprotected heavy rectangular cross-sections, these results contribute to a better understanding of the mechanical behaviour caused by elevated temperature and the modelling of it. This is partly due to the use of light members where the influence of some parameters is more evident, partly due to the partial protection of the members which allows one to seperate the influence of certain parameters.

The aim of the investigation was to study the strength and stiffness properties of protected light timber frame members as they are used in walls and floors. The flat sides of the members with the dimensions 45 x 145 mm^2 were protected by rockwool insulation. The members were exposed to standard fire according to ISO 834 on one narrow side and were in pure edgewise bending in the region inside the furnace. Two different load directions occurred. In test series No. 1 the fire-exposed side was in compression and in series No. 3 in tension. The applied loads were in the range between 10 and 77 % of the predicted ultimate load at normal temperature. In test series No. 2 the fire-exposed side of the members was in compression and, initially, protected by gypsum plasterboard.

Summary of results

The results presented in /4/ can be summarized as follows:

a) The relationship between relative load and failure time can be expressed by exponential functions, which are dependent on whether the fire-exposed side is in compression or tension.

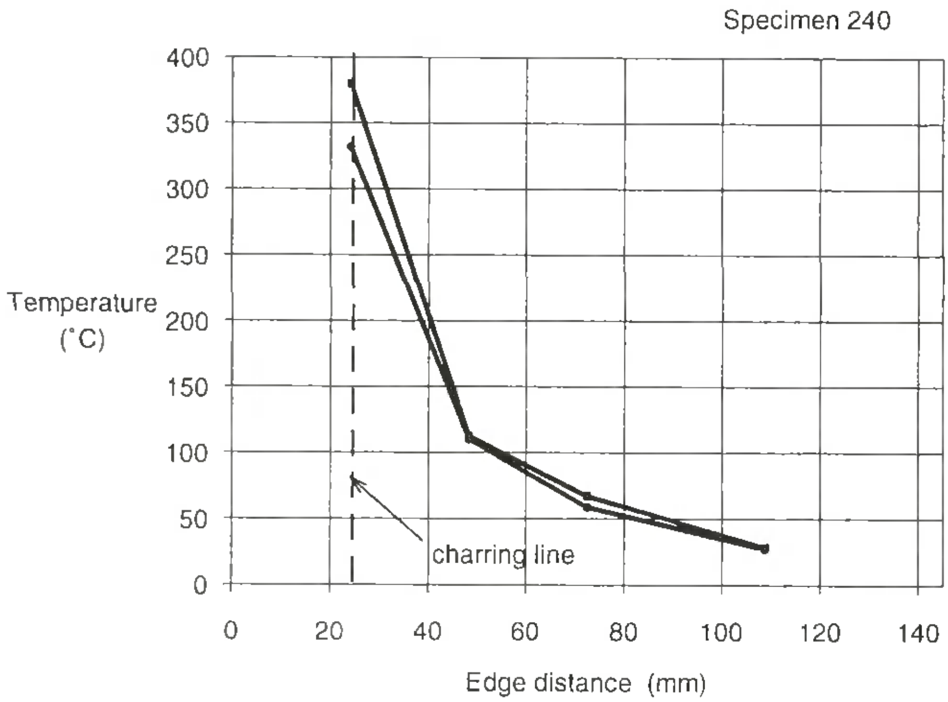
b) The loss of flexural stiffness is considerably larger when the fire-exposed side is in compression. This is more pronounced when the load level is high, but is negligible at load levels below about 35 % of predicted ultimate load at normal temperature. When the fire-exposed side is in tension flexural stiffness is independent of load level.

c) The position of the neutral axis is dependent of whether the fire-exposed side is in compression or tension. In the case of compressive stresses a large portion of the residual section on the fire-exposed side is statically ineffective due to plastic deformations while this ineffective portion is smaller in the case of tensile stresses.

d) The influence of the gypsum plasterboard lining is purely additive. It can be expressed by a displacement of the exponential function mentioned above in (a) in direction of the time-axis.

Additional results

Temperature and charring line. Some additional results are given below. A typical temperature profile along the centre line of the cross section and the corresponding residual uncharred core after fire-exposure of 30 minutes is shown in Figure 1. The thermo-couples were attached on the centre line of the cross section at different sections at equal distances of 100 mm. The location of the charring line at the centre line of the cross section is plotted in the diagram with a dotted line. It is widely accepted



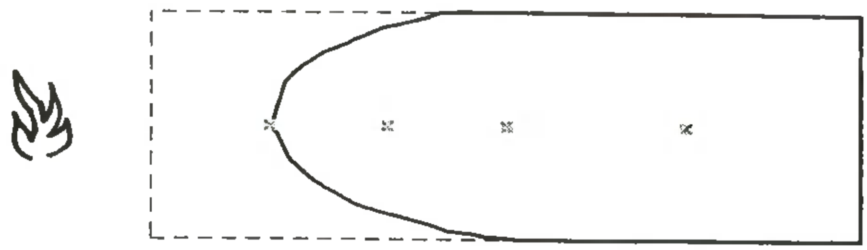


Figure 1 Example of temperature profile along the centre line of the cross section at failure.

that charring occurs at a temperature of about 280 °C. The diagram coincides fairly well with this. The plotted charring line is the mean value of the recorded values from five different sections, which were different from the positions of the thermo-couples.

The propagation of temperature with time can be seen from Figure 2. This diagram shows the two recorded temperature profiles at ultimate state of all specimens in Series No. 3 (fire-exposed side under tensile stresses). The failure times were in the range from 10 to 50 minutes. The vertical axis of the diagram is cut at 300 °C. The intersection of the temperature curves with this level indicates the approximate location of the charring line at the centre line of the cross section. From the diagram it can be seen that the temperature gradient is very steep close to the charring line. In the main part of the uncharred core temperature is considerably below 100 °C.

Three additional tests with unloaded specimens were made in order to measure temperature profiles perpendicular to the centre line, since it could be expected that the thermal flow would be greater in the mineral wool than in the wood. Some typical results can be seen in Figure 3.

The experimental charring depths at the centre line of the cross section are shown in Figure 4. In series No. 2 charring is delayed due to the attached gypsum plasterboard lining on the fire-exposed side of the member. Considering charring depths greater than about 20 mm the delay of charring coincides well with the delay of the loss of load capacity and stiffness. See Figure 6 in /4/.

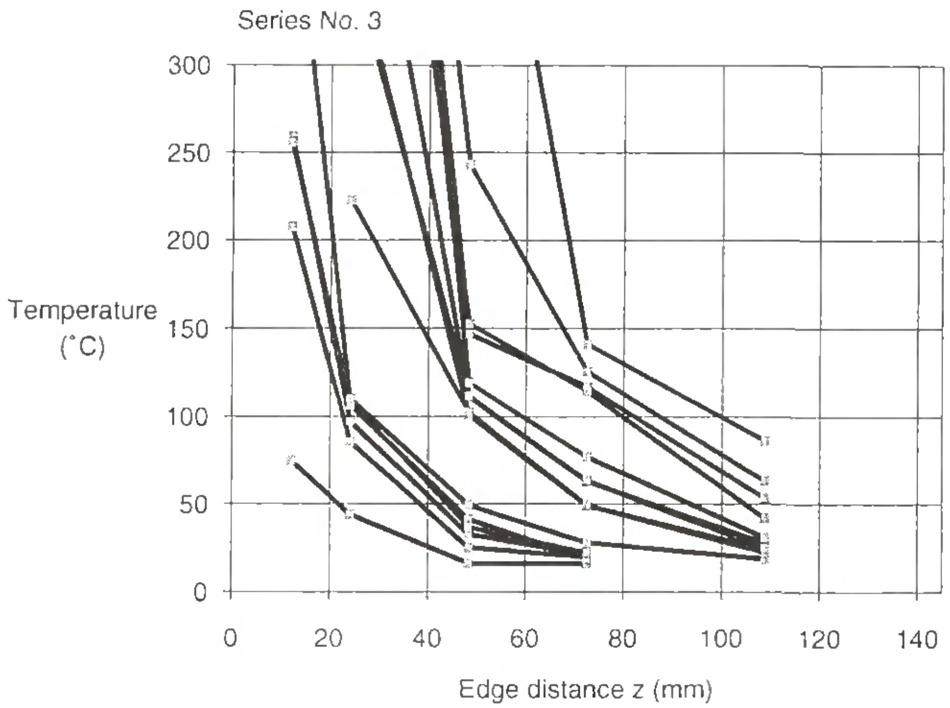
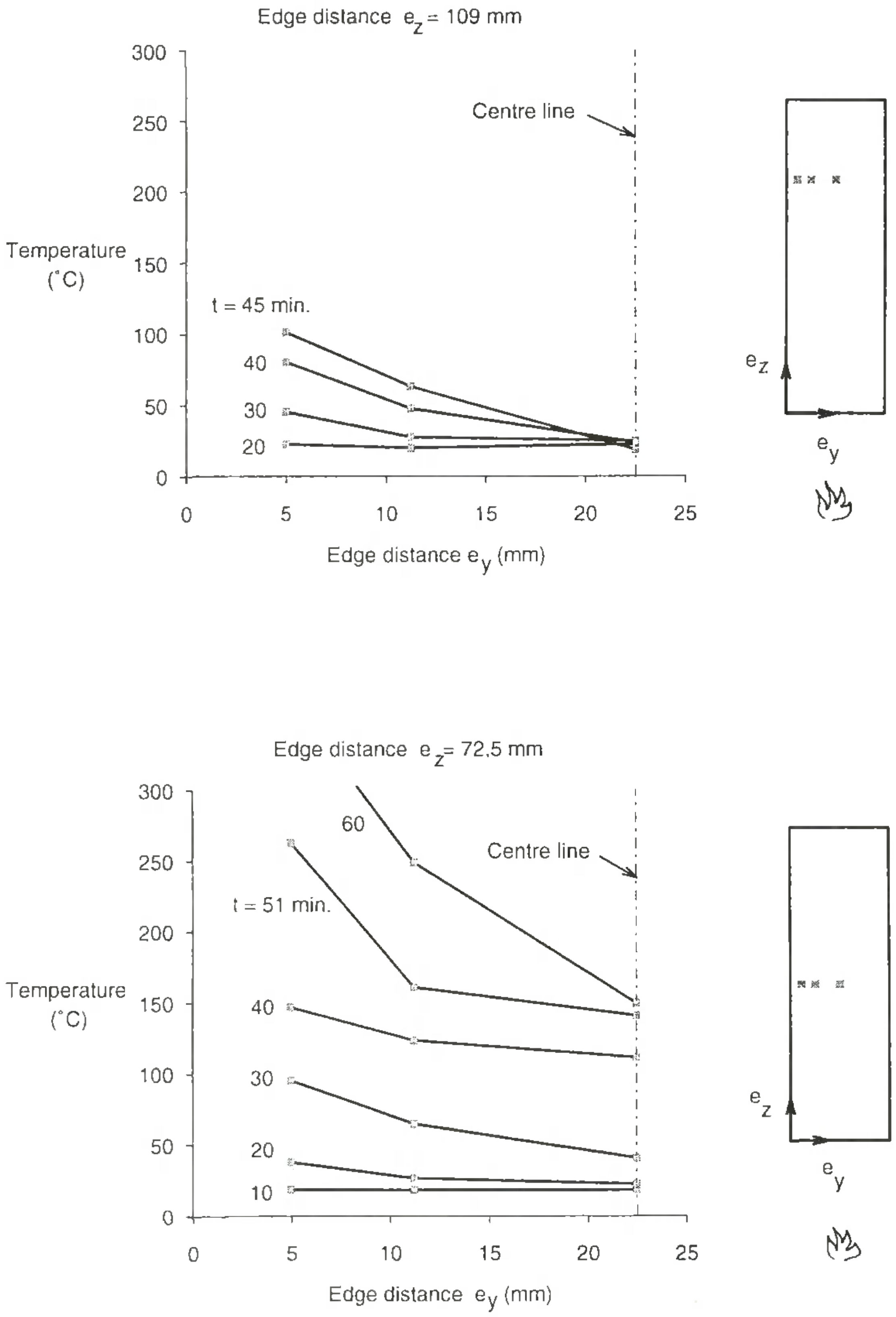


Figure 2 Temperature distributions of test specimens of Series No. 3 at failure.

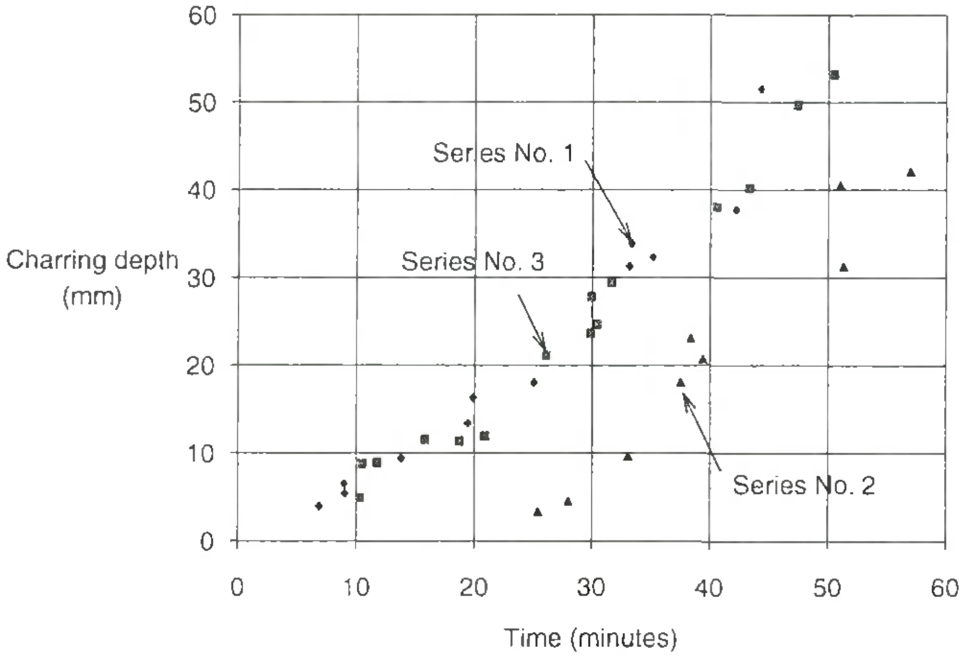


<u>Figure 3</u> Temperature profiles perpendicular to the centre line of the cross section at different times.

Experimental charring rates valid for the centre line of the cross section were determined. See Figure 5. The charring rates were calculated using the minimum edge distance which was normally not exactly on the centre line of the cross section. The squares refer to measured values while the triangles refer to standardized time values with respect to density, see /4/. Both regression lines are almost identical.

The experimental charring rates are in the range between about 0.5 and 1 mm per minute, which is the range mentioned in the introduction of this paper. In contrast to recorded charring rates in heavy timber, the charring rate increases with time. This is due to the fact that the heat flow in the beginning is one-dimensional, while it becomes increasingly more and more two-dimensional, c.f. Figure 3. This effect is increased since the mineral wool insulation is destroyed close to its surface. C.f. the shape of the uncharred core in Figure 3 in /4/.

<u>The influence of density.</u> In /4/ exponential regression curves were calculated, describing the relationship between relative load capacity and failure time. In order to investigate the influence of density on the loss of load capacity, the specimens of series No. 3 were divided into two groups, the first one containing specimens with densities below mean density, and the second one



<u>Figure 4</u> Experimental charring depths at the centre line of the cross section. In series No. 2 a gypsum plasterboard lining is attached to the member.

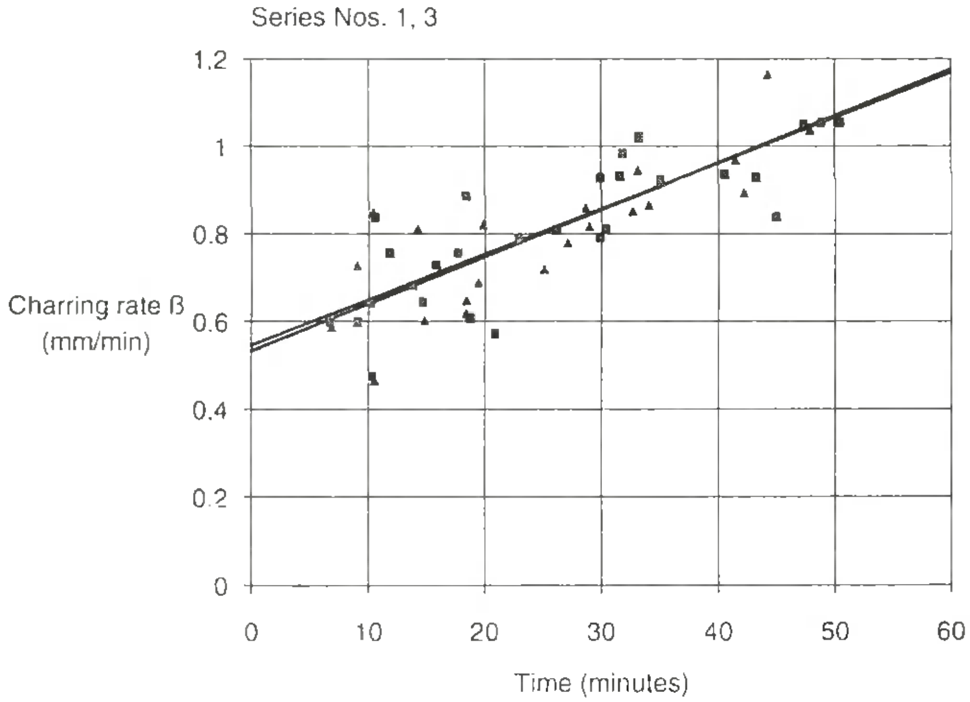


Figure 5 Experimental charring rates in series Nos 1 and 3 at the centre line of the cross section. Squares refer to real time and triangles refer to standardized time with respect to density.

containing specimens with densities above mean density. The ratios of ρ/ρ_{mean} were 0.939 and 1.053 respectively. For each of these groups exponential regression curves were determined by using real time values. The statistical difference of these two curves is significant at the level of 5 %. The same procedure was followed using standardized time values with respect to density, assuming that
failure time is inversely proportional to density. In this case no significant difference of the corresponding curves was obtained. Thus the influence of density can be taken into account by standardizing failure time with respect to density as described.

The influence of loading rate. In fire tests the applied load is normally held constant until failure. Since the effective cross section is decreasing during the test, strains and stresses increase initially at a very slow and approximately constant rate. Only in the stage close to failure do these rates accelerate more and more. This can be seen from the relationships between deflection and time. See Figures 4b and 5b in /4/. In design by testing it would facilitate the determination of load capacity for a specific fire resistance by increasing the applied loading during the fire test.

In order to investigate the influence of the loading rate, additionally to the tests in series Nos 1 and 3 a number of tests were performed in which the applied load was increased before failure. In these tests different, initially constant loads were applied, at relative load levels between 0 and 25 %. Near the end of the tests the load was increased at a rate of approximately 25 % of the load capacity at normal temperature per minute. The time-

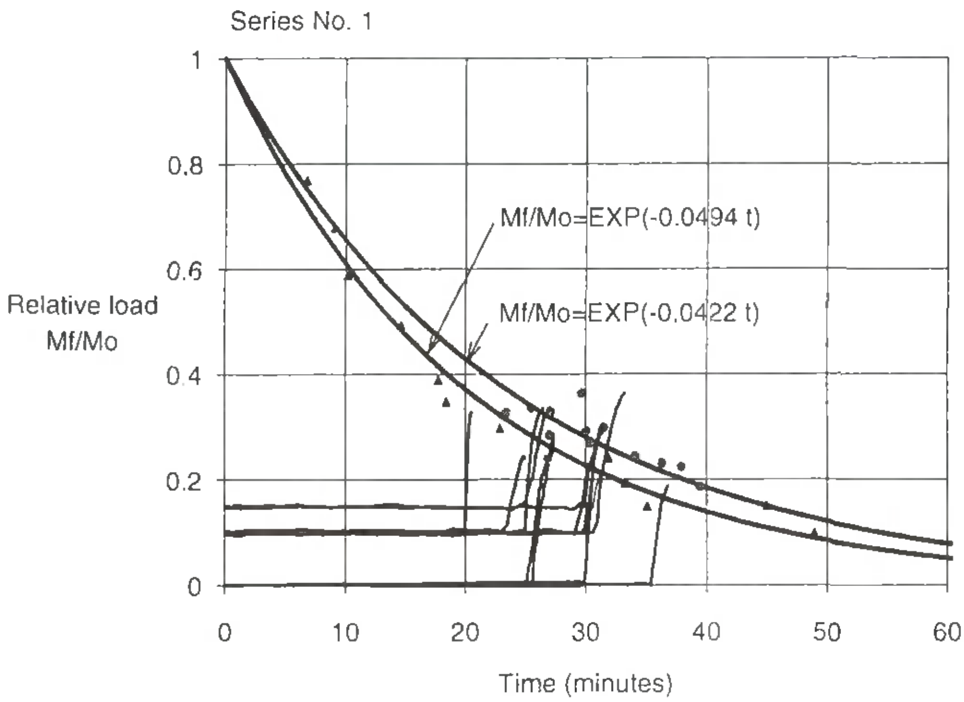


Figure 6 The influence of loading rate on load capacity in series No 1 (fire-exposed side in compression). For specimens with load increasing the whole load-path is plotted.

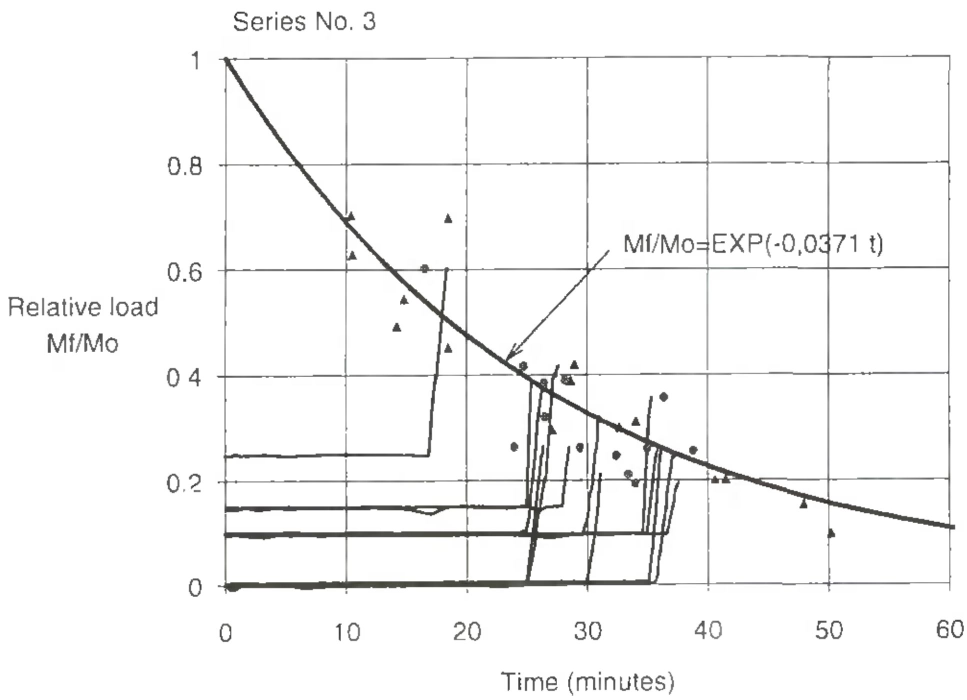


Figure 7 The influence of loading rate on load capacity in series No 3 (fire-exposed side in tension). For specimens with load increasing the whole load-path is plotted.

paths during the tests are shown in Figures 6 and 7. The end-points of these curves are also shown for standardized time values with respect to density as circles, together with corresponding exponential regression curves. These figures correspond to Figures 4a and 5a in /4/. In order to improve legibility of the figures only standardized time values are shown (triangles) with reference to specimens with constant load.

These test results show that the loading rate only exerts an influence in the case of compressive stresses on the fire-exposed side (Series No.1, Figure 6). The difference of the two curves in Figure 6 is statistically significant at the level of 0,2 %, while it is not significant in Figure 7. Thus, determining the ratio of the two regression curves of Figure 6 we get the loading rate coefficient

$$\kappa_l = e^{0.0072\,t}$$

which the load capacity is multiplied by when the fire-exposed side is in compression.

An explanation of this different behaviour is that wood is more sensitive to creep when it is in compression. This phenomenon is more accentuated at elevated temperature.

MODELLING

"Exact" approach

In principal there are two alternative methods of determining the load bearing capacity and stiffness properties of a wood member in fire. The most exact way would be to determine the real charring line and the temperature and moisture content field in the residual core. With corresponding strength and stiffness data for the material it would then be possible to calculate the properties of the uncharred cross section, even though the procedure would be tedious.

For the time being there is insufficient data on the influence of elevated temperature on the strength and the modulus of elasticity of wood. Recently short-term tests have been performed in order to determine the strength and modulus of elasticity of timber in tension, compression and bending at elevated temperature /5/. The test results referred to above show that there exists an influence of time due to excessive creep in the compressed part of the cross section when the temperature is elevated. In order to use an "exact" approach it would be necessary to introduce modification and creep factors which allow the accentuated influence of time at elevated temperature to be taken into account.

An "exact" method would be most adequate when applied to homogeneous or quasi-homogeneous materials such as LVL (laminated veneer lumber) or glulam timber. In solid timber strength is actually, due to the importance of defects, a reference value, calculated in order to fit test results, assuming that the material is homogeneous and stress varies linearly across the depth. As long as this engineering approach is used in "cold design" of solid timber there should be no advantage in using a more exact method in "hot design". It should have its main application for research purposes.

Engineering approach

General. The other alternative is an engineering approach which is much easier for the designer to apply. In "cold design" such an approach is applied by replacing the complex behaviour of timber. Thus in bending, fitted reference values of flexural strength and modulus of elasicity are used in order that timber can be regarded as a homogeneous and purely elastic material. An engineering approach in "hot design" should give rules on how the effective cross section of a member should be determined in order that the same design rules which are common in "cold design" can be used. Such a model should fulfil the following requirements:

a) The model should be easily usable by the designer.

b) It should be able to give values of relevant effective cross section data, e.g. with respect to strength, stiffness and the position of the centre of gravity.

c) The model should not pretend an accuracy which does not exist.

d) Limits of validity should be given.

e) The formulation of the model should be sufficiently general in order to be able to fit future applications beyond its present limits.

f) It should be compatable with design by testing, i.e. it should be possible to determine parameters in the model from test results.

In such a model the real charring rate is replaced by a notional or effective one which is a calibrated value in order to fit test results, taking into account effects of charring, elevated temperature, moisture content and creep. Since there are, apart from charring, several other parameters which influence the loss of load capacity and stiffness, the term charring rate should be replaced by another term which takes account of this.

The test results referred to above describe the behaviour of light structural members which are different from those the rules in the present codes generally apply to. In fire tests of heavy members normally three or four sides were exposed to fire. It was therefore difficult to see that the effective charring rate is influenced by the type of loading. In practical applications with the same type of fire-exposure this different behaviour can be disregarded since the applied charring rate represents some kind of mean value.

Shape of effective section. As a consequence of requirement (a) the simplest shape of the effective section should be rectangular with reduced depth and unreduced width, i.e. due to the protection of the flat sides of the member it is assumed that only the depth of the section is affected by charring, even though this assumption differs considerably from the shape of the real uncharred core. See Figure 1. As a consequence of requirement (b) notional charring rates were determined in order to fit section modulus, flexural stiffness and the position of the centre of gravity.

Load bearing capacity at failure time. Notional charring rates were calculated in order to fit the failure times obtained in the tests. See Figures 8 and 9. These calculations were made assuming full and reduced strength respectively. In the case of a loss of strength it was reduced to 75 %, 55 % and 40 % when the fire-exposed side was in compression, and to 90 % and 75 % when the fire-exposed side was in tension. In the present EC5 draft /3/ reduced strength and stiffness values are given, based on /5/. When the bending strength was unreduced ($f=f_m$) - the single values are marked by squares in the figures - linear regression curves were calculated, for each load direction. When reduced strength was assumed the notional charring rate values at the beginning of the tests were disregarded in calculating regression lines.

The results show that the notional charring rates β_n are more or less time-dependent. When the expressions obtained for unreduced strength, i.e.

$$\beta_n=3.266-0.0237\ t$$

and

$$\beta_n=2.571-0.0157\ t$$

respectively were used in calculating load capacity-time relationships, the curves obtained were almost identical to the experimental regression curves. In order to simplify the model a constant notional charring rate should be chosen which gives the best fit in the region of working load. For some assumed notional charring rates β_n relationships of relative load capacity and failure-time were calculated. See Figures 10 and 11. It is obvious that a constant charring rate does not agree very well with the experimental regression curve when unreduced strength is assumed.

The best agreement between the model and the experimental regression curves at relative loads below about 30 % is obtained by assuming a notional charring rate of 1.7 mm/min and a strength reduction of 55 and 75 % respectively. The best agreement for all load levels should be obtained by assuming an increasing reduction of strength with time. This would descibe the real behaviour best but make the model overly complicated.

Flexural stiffness. When the flexural stiffness is used in calculating the buckling load of a member in axial compression, it is necessary to describe its effective cross section during the whole time period of fire-exposure. From Figures 3 and 4 it can be seen that considerable temperature variations exist both at different points of the uncharred cross section and over time. This makes it more complicated to model stiffness. The easiest way to take into account the softening of the material is to choose a larger notional charring rate. Therefore calculations of the relative flexural stiffness were made only for the case of unreduced modulus of elasticity.

Assuming the expression of notional charring rate which fits the load capacity best during the whole time period of the tests, the curves (1) in Figures 12 and 13 were obtained. The dotted experimental curves are identical with those shown in Figures 4c and 5c in /4/. The curves (2) refer to constant average notional charring rates. The difference between the curves (1) and (2) is not very large. The curves (3) were obtained by choosing constant

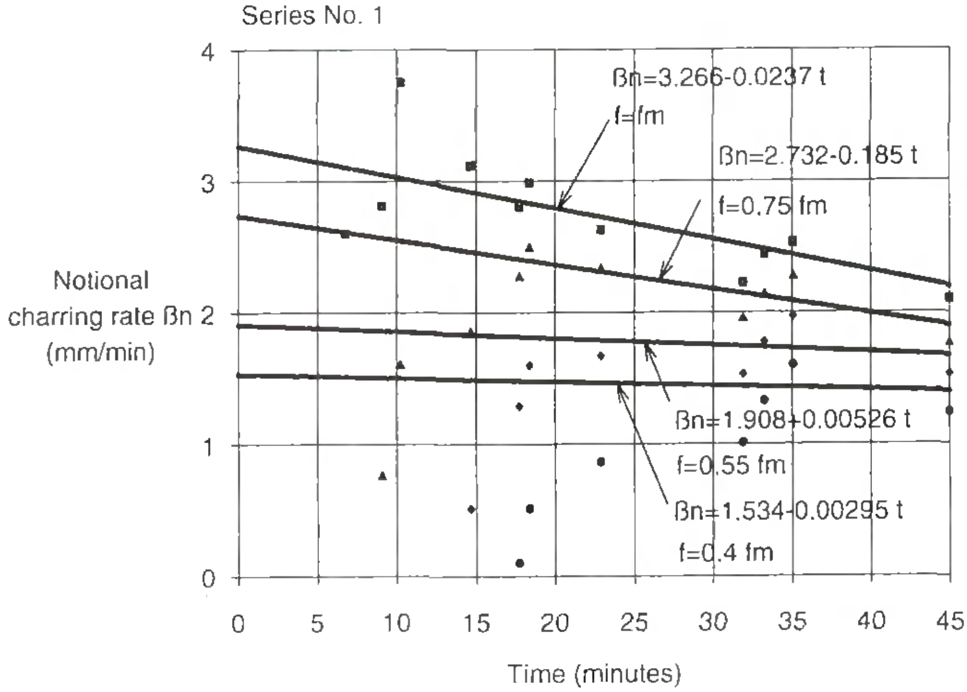


Figure 8 Experimental notional charring rates in series No.1 (fire-exposed side in compression) for ultimate load capacity at failure time.

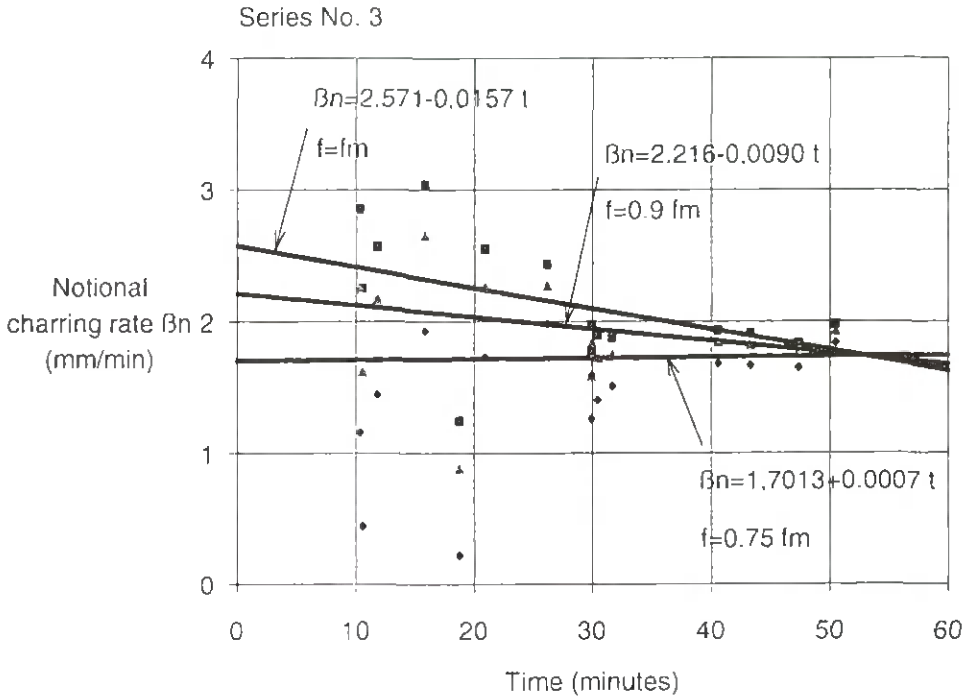


Figure 9 Experimental notional charring rates in series No.3 (fire-exposed side in tension) for ultimate load capacity at failure time.

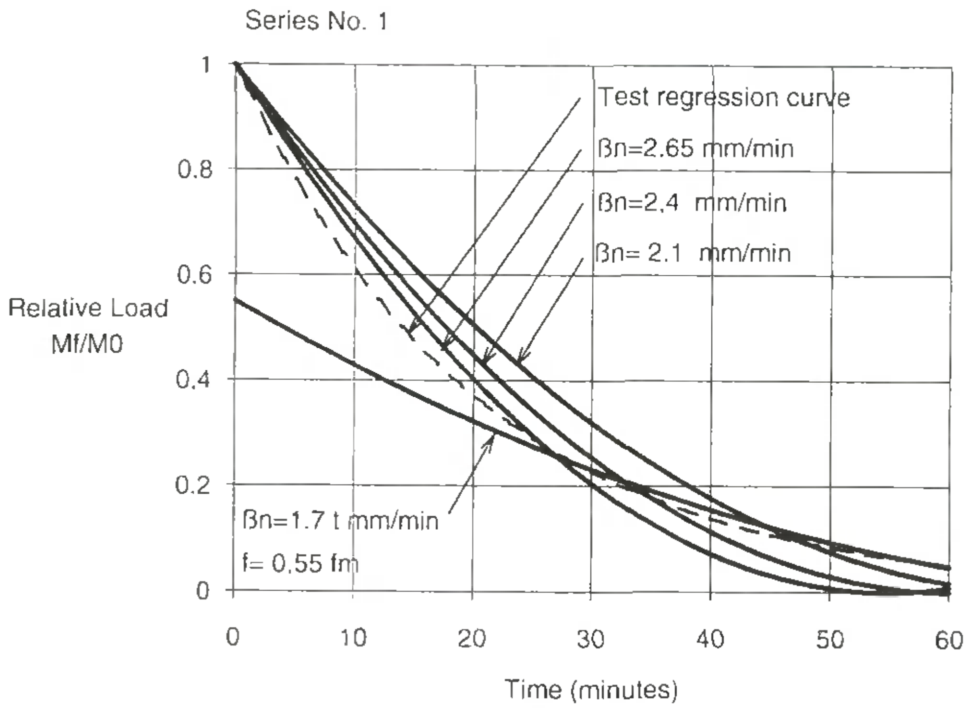


Figure 10 Calculated curves of relative load capacity versus failure time in series No. 1 (fire-exposed side in compression).

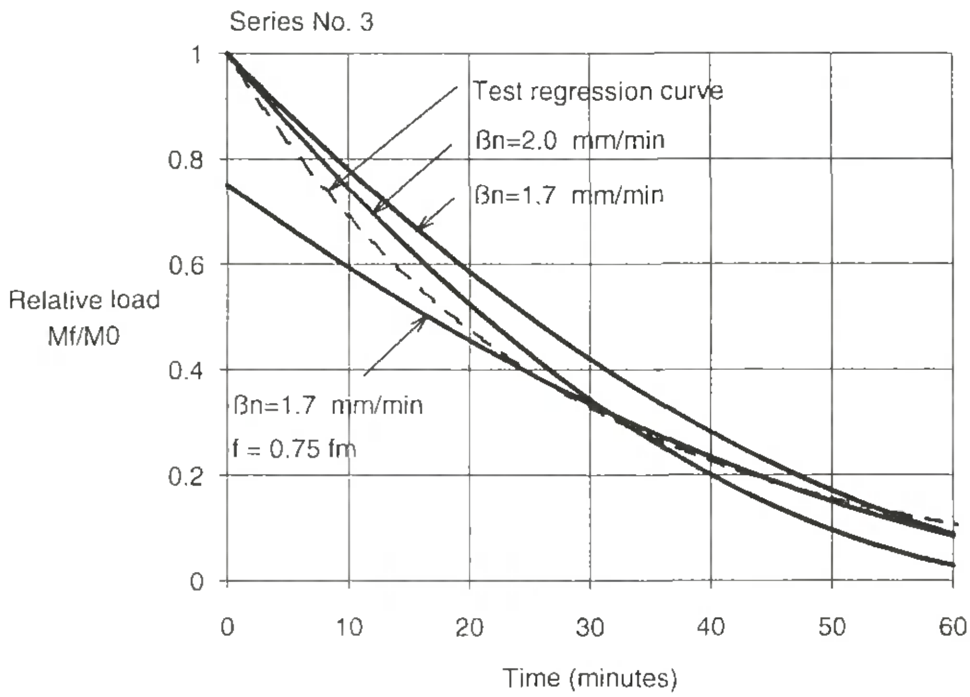


Figure 11 Calculated curves of relative load capacity versus failure time in series No. 3 (fire-exposed side in tension).

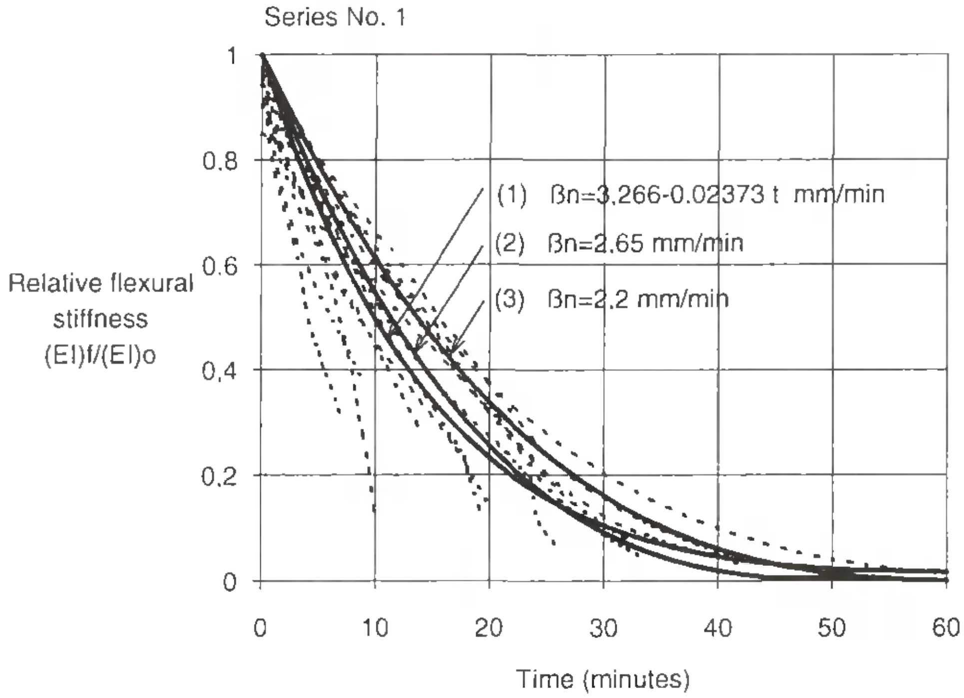


Figure 12 Comparison of calculated and experimental curves of relative flexural stiffness versus time in series No. 1 (fire-exposed side in compression).

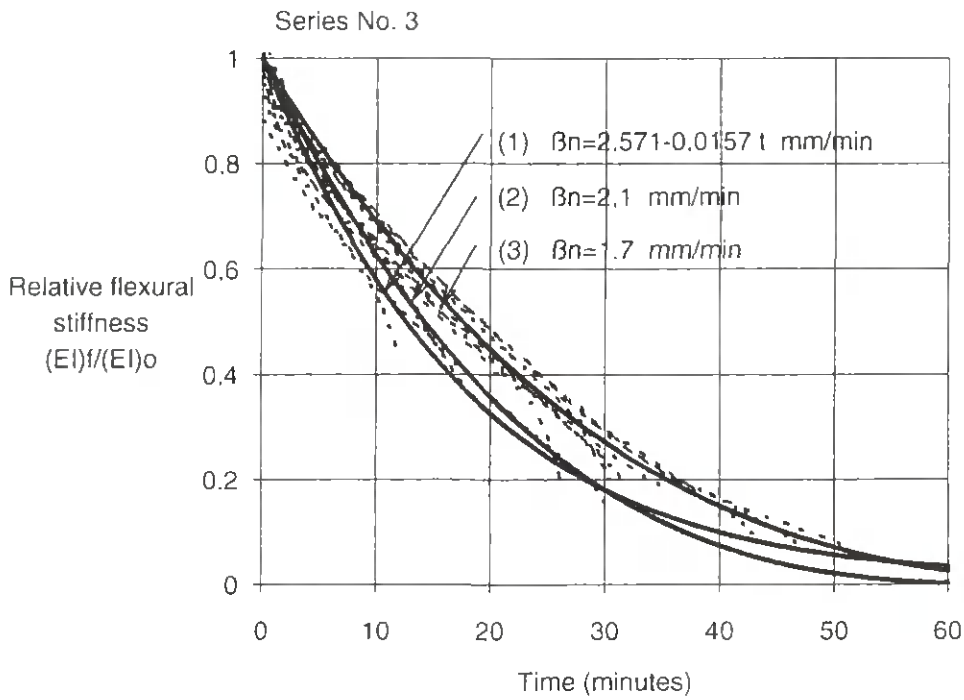


Figure 13 Comparison of calculated and experimental curves of relative flexural stiffness versus time in series No. 3 (fire-exposed side in tension).

notional charring rates which best best the experimental curves. In the case of tensile stresses a notional charring rate of 1.7 mm/min gives good agreement, the same value that has been found to give reasonable results when bending load capacity is calculated at working load levels. When the fire-exposed side is in compression the best agreement is obtained by using a notional charring rate of 2.2 mm/min., i.e. about 30 % greater than in the case of tensile stresses.

Position of centre of gravity. In axially loaded members the determination of second order moments is essential. Thus it is essential that the model is adequate with respect to the location of the centre of gravity. The position of the centre of gravity of the test specimens was determined assuming notional charring rates giving the best agreement between the experimental and calculated flexural stiffness, i.e. curves (3) above. From Figures 14 and 15 it can be seen that the agreement between calculated and test data is fairly good, except in those cases of series No. 1 when the relative load is high (more than 30 %), or the residual stiffness is very small. These cases are outside practical applications. The results show that the assumption of a rectangular shape of the effective cross section is reasonable.

Protection by lining. From the test results, it can be seen that the effect of a lining is purely additive, i.e. there exists a delay of charring, see Figure 5, and consequently also of the loss

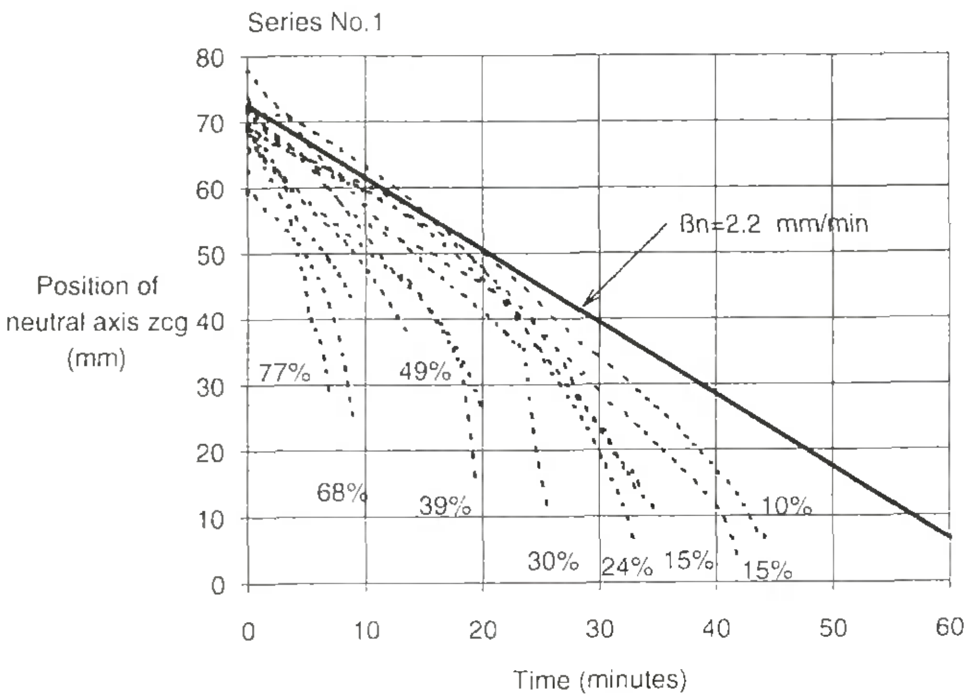


Figure 14 Comparison of calculated and experimental curves of the distance of the neutral axis from the uncharred side versus time in series No. 1 (fire-exposed side in compression).

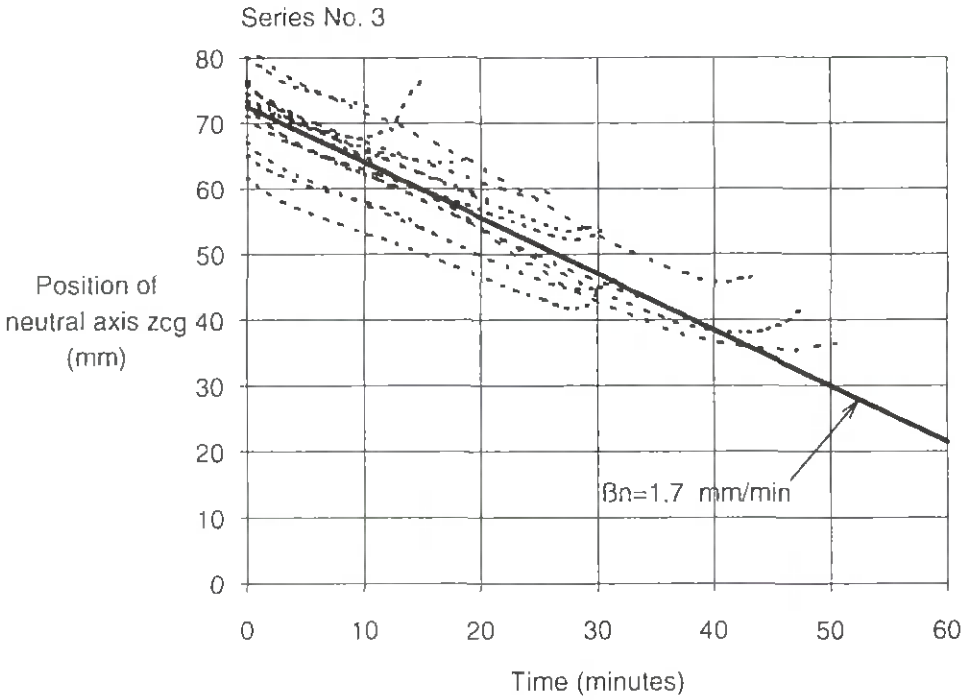


Figure 15 Comparison of calculated and experimental curves of the distance of the neutral axis from the uncharred side versus time in series No. 3 (fire-exposed side in tension).

of load capacity and flexural stiffness, see Figure 6 in /4/. Thus it is easy to consider the effect of claddings by using the delay which is specific for the lining either with the concept of notional or real charring rates.

Conclusions. It is obvious that, in general, different notional charring rates should be used for modelling the effective section, not only with respect to load capacity and stiffness but also with respect to the state of stresses. In many applications this distinction is not necessary as in the case of fire-exposure on four sides or of very large sections. While in calculations of bending load capacity a loss of strength should be taken into account, it is not necessary to regard the loss of the modulus of elasticity when the flexural stiffness of the member is determined. Therefore in design rules notional charring rates should be linked together with rules about, whether, or how much the strength and the modulus of elasticity has to be reduced. In the case of the specimens of the investigation refered to here, it was possible to use only two different charring rates in connection with different reductions of strength and modulus of elasticity. See Figure 16. In other applications this may be different.

Assuming a simple effective cross section of rectangular shape it is possible to achieve good agreement between calculated and test results. It is therefore unnecessary to introduce rounded edges in the model. In most cases the increase in accuracy of the model should be illusory whilst its use would be more complicated.

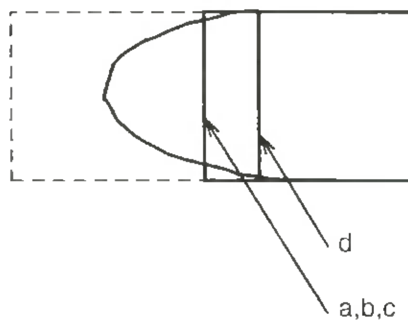


Figure 16 Effective cross sections for uncharred core shown in Figure 1 linked to the following assumptions:
a) Ultimate load - fire-exposed side in tension - $f=0.75\ f_m$
b) Ultimate load - fire-exposed side in compression - $f=0.55\ f_m$
c) Flexural stiffness - fire-exposed side in tension - E not reduced
d) Flexural stiffness - fire-exposed side in compression - E not reduced

By using the notional charring concept it is possible to specify expressions which are specific to different applications. Thus the concept is sufficiently general and should be useful in future applications.

REFERENCES

/1/ Meyer-Ottens, C., Feuerwiderstandsdauer unbekleideter hoher Rechteckbalken aus Brettschichtholz. Published in Forschungsbeiträge für die Baupraxis, Karl Kordina zum 60. Geburtstag gewidmet. Wilhelm Ernst & Sohn, Berlin, 1979.

/2/ Hall, G.S., Fire resistance tests of laminated timber beams. Trada Research Report WT/RR/1, High Wycombe, 1968.

/3/ Eurocode No.5, Part 10: Structural Fire Design. Draft April 1990. Commission of the European Communities.

/4/ König, J. & Norén, J., Fire tests on timber frame members under pure bending. 1991 International Timber Engineering Conference, London.

/5/ Glos, P. & Henrici, D., Festigkeit von Bauholz bei hohen Temperaturen. Institut für Holzforschung der Universität München, 1990.

SAMMANFATTNINGAR

Träreglar vid ren böjbelastning brandprovades i en modellugn. Provkropparna var sammansatta av själva träregeln och omgivande material såsom stenull och skivor representerade termiska förhållanden som är typiska i golv och ytterväggar. Det bestämdes samband mellan bärförmågan och tiden till brott, böjstyvheten och neutrala lagrets läge. Det observerades att bärförmågan och styvheten är beroende av lastriktningen, samt, när den brandutsatta sidan är tryckt, även av lastnivån.

Resultaten från brandprovning av delvis skyddade träreglar vid ren böjning används i syfte att medelst en analytisk modell beskriva det effektiva tvärsnittet hos denna typ av träregelkonstruktioner. Provningsresultaten gjorde det möjligt att beakta inverkan av några parametrar såsom lastnivån i förhållande till bärförmågan vid normal temperatur, spänningstillståndet, belastningshastigheten och träets densitet. Analytiska modeller diskuteras därför i ett vidare perspektiv och några konsekvenser avseende kraven på en analytisk modell är beskrivna.

Detta digitala dokument
skapades med anslag från

**Stiftelsen Nils och Dorthi
Troëdssons forskningsfond**

Trätek

INSTITUTET FÖR TRÄTEKNISK FORSKNING

Box 5609, 114 86 STOCKHOLM
Besöksadress: Drottning Kristinas väg 67
Telefon: 08-762 18 00
Telefax: 08-762 18 01

Åsenvägen 9, 553 31 JÖNKÖPING
Telefon: 036-30 65 50
Telefax: 036-30 65 60

Skeria 2, 931 77 SKELLEFTE
Besöksadress: Laboratorgränc
Telefon: 0910-652 00
Telefax: 0910-652 65