The reduced cross-section method for light timber frame construction with solid timber members

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Abstract

A numerical study was conducted with the objective of developing an alternative to the existing reduced properties method for calculating the resistance in bending or axial loading of fire exposed solid timber members in wall and floor assemblies. The alternative method, called reduced cross-section method, uses zero-strength layers instead of modification factors for fire to take into account the reduction of strength and stiffness properties of the residual cross-section. Simple expressions were derived for the calculation of zero-strength layers by fitting to the existing method.

Key words: assemblies, design, fire, floors, resistance, strength, timber structures, walls,

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Preface

This study was conducted at SP Trätek, Stockholm, as a part of the FireInTimber project within the European Wood-Wisdom-Net framework. It is supported by industry through the European Initiative Building With Wood and public funding organisations.

Summary

In timber members exposed to fire a zone of about 35 to 40 mm depth below to the char layer, although unburned, is heated above ambient temperature. Due to the elevated temperature this zone, strength properties and the modulus of elasticity of the residual cross-section must be reduced. Two methods, known as reduced properties method and reduced cross-section method, respectively, are used in practice. In the first one the strength and stiffness properties of the cross-section, e.g. bending strength or modulus of elasticity, are multiplied by modification factors for fire, while in the second one, the residual cross-section is reduced by a so-called zero-strength layer, whereas the strength and stiffness properties remain unreduced.

For the calculation of mechanical resistance in fire of timber frame members in wall and floor assemblies with cavities filled with insulation, EN 1995-1-2 gives a design model using the reduced properties method. In order to simplify the calculation the original data were re-evaluated and expressions for zero-strength layers were derived to allow the use of the reduced cross-section method. For bending, the zero-strength layers were calculated to achieve the best fit of bending resistance in the range of load ratios between 0,2 and 0,4. Only for load ratios smaller than 0,2 the results are slightly non-conservative. For axially loaded members, the zero-strength layers were determined to give the same or lower bending stiffness than according to the reduced properties method. The axial resistance of studs, however, calculated using the method of EN 1995-1-1 with properties relevant for the fire situation, is somewhat greater when the reduced cross-section method is used.

1 Introduction

1.1 General

In timber members exposed to fire a zone of about 35 to 40 mm depth below the char-layer of the residual cross-section, although unburned, is heated above ambient temperature. This elevation of temperature gives rise to reduced strength and stiffness properties of the timber in this zone. EN 1995-1-2 [1] gives design values for strength and stiffness properties for timber members (e.g. beams or columns) as:

$$f_{\mathrm{d,fi}} = k_{\mathrm{mod,fi}} \frac{f_{20}}{\gamma_{\mathrm{M,fi}}} \tag{1.1}$$

$$S_{\mathrm{d,fi}} = k_{\mathrm{mod,fi}} \frac{S_{20}}{\gamma_{\mathrm{M,fi}}} \tag{1.2}$$

where:

$f_{\mathrm{d,fi}}$	design strength in fire (bending strength, compressive strength etc of timber members);
$S_{\mathrm{d,fi}}$	design stiffness property (modulus of elasticity $E_{\mathrm{d,fi}}$ or shear modulus $G_{\mathrm{d,fi}}$) in fire;
f_{20}	20 % fractile of a strength property at normal temperature;
S_{20}	20 % fractile of a stiffness property (modulus of elasticity or shear modulus) at normal temperature;
$k_{\mathrm{mod,fi}}$	modification factor for fire taking into account the reduction in strength and stiffness properties at elevated temperatures;
$\gamma_{\mathrm{M,fi}}$	partial safety factor for timber in fire ($\gamma_{\mathrm{M,fi}} = 1$).

The 20 % fractile of a strength, and correspondingly of a stiffness property, is derived from the characteristic (5 % fractile) value as

$$f_{20} = k_{\mathrm{fi}}\ f_{\mathrm{k}}$$

where k_{fi} is dependent on the coefficient of variation of the material. For example, for solid timber k_{fi} = 1,25, for glued laminated timber k_{fi} =1,15.

For the design procedure for mechanical resistance, for the determination of cross-section properties, i.e. the determination of strength and stiffness properties, EN 1995-1-2 [1] gives two alternative methods:

- the reduced cross-section method
- the reduced properties method.

The reduced properties method is a direct application of the general expressions given above for design values for strength and stiffness properties. For specific structural members modification factors for fire, $k_{\mathrm{mod,fi}}$, are given (beams, columns, timber frame members in insulated wall and floor assemblies). The reduced strength and stiffness properties are to be applied to the residual cross-section, i.e. the original cross-section reduced by the depth of the char-layer. In order to simplify the calculation, notional charring depths are used and the residual cross-section is therefore rectangular.

As an alternative, for beams and columns, the effective cross-section method allows for further simplification of the design. This method, permitting the designer to use “cold” strength and stiffness properties (with $k_{\mathrm{mod,fi}} = 1$ in equations (1.1) and (1.2)) and an effective residual cross-section, taking into account the reduction of strength and stiffness in the heat affected zones by removing a further 7 mm thick layer from the residual cross-section. It is assumed that this zero strength layer is built up linearly with time during the first 20 minutes of fire exposure, or, in case of a fire protective layer being applied to the timber member, during the time period until the start of charring.

1.2 Timber frame studs and joists

Designers in practice seem to prefer the reduced cross-section method since it is simpler to use. For the design of timber frame wall and floor assemblies with cavities filled with insulation, however, EN 1995-1-2 [1] only gives modification factors $k_{\text{mod,fi}}$. The application of the 7 mm zero-strength layer is not permitted since the results would be unsafe. The modification factors $k_{\text{mod,fi}}$ are dependent on the cross-section properties and state of stress on the fire exposed side, i.e. tension or compression, and the charring depth. They are given as linear expressions of shape

$$k_{\text{mod,fi}} = a_0 + a_1 \frac{d_{\text{char,n}}}{h} \tag{1.3}$$

with parameters a_0 and a_1 given for specific member depths h in a number of tables. For simplicity, the values for b = 38 mm were assumed also for other values of b. For other depths these parameters are determined by linear interpolation.

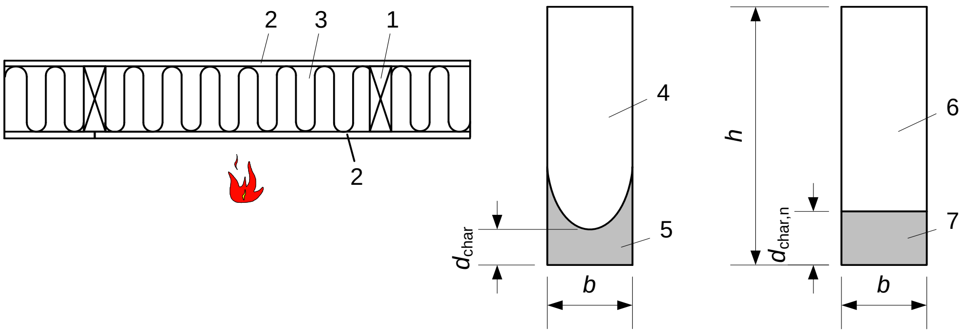
The notional charring rate, $d_{\text{char,n}}$, is determined as

$$d_{\text{char,n}} = k_{\text{n}}\ d_{\text{char}} \tag{1.4}$$

with

$$k_{\text{n}} = 1{,}5 \tag{1.5}$$

see Figure 1.1.



a) b) c)

Key:

1	Solid timber member (stud or joist)
2	Cladding
3	Insulation
4	Residual cross-section (real shape)
5	Char-layer (real shape)
6	Equivalent residual cross-section
7	Char-layer with notional charring depth

Figure 1.1 – Charring of timber frame member (stud or joist): a. Section through assembly. b. Real residual cross-section and char-layer. c. Notional charring depth and equivalent residual cross-section.

The background of the method given above is given in [2]. In the following section the results of calculations in [2] are re-evaluated with the aim of deriving zero-strength layers for the application of the reduced cross-section method to timber frame members with rectangular cross-sections.

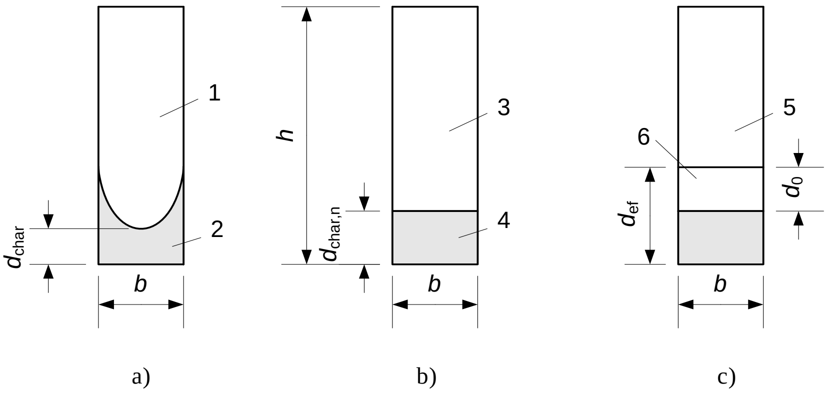
2 Zero-strength layers of timber frame members

2.1 General

The effective cross-section used in the following is defined in Figure 2.1, i.e. it is obtained by increasing the notional charring depth by the zero-strength layer d_0:

$$d_{\mathrm{ef}} = d_{\mathrm{char,n}} + d_0 \tag{2.1}$$

No further reduction of the cross-section is done on the wide sides of the cross-section.



Key:

1	Residual cross-section
2	Char layer
3	Notional (equivalent) cross-section
4	Notional char-layer
5	Effective cross-section
6	Zero-strength layer below char-layer

Figure 2.1 – Definition of charring depth, notional charring depth, effective charring depth and zero-strength layer.

2.2 Members in bending (floor joists)

The modification factors $k_{\mathrm{mod,fi}}$ given in [1] were derived in [2]. For simplicity, the non-linear relationships of $k_{\mathrm{mod,fi}}$ versus the relative charring depth d_{char}/h were replaced by linear trendlines, see Figure 2.2. It can be seen that the linear relationship is slightly non-conservative in the range of load levels between 20 and 40 %, which is most relevant in practice. In order to obtain a better agreement, in the following the zero-strength layer was determined from the relationships of relative bending moment versus relative charring depth.

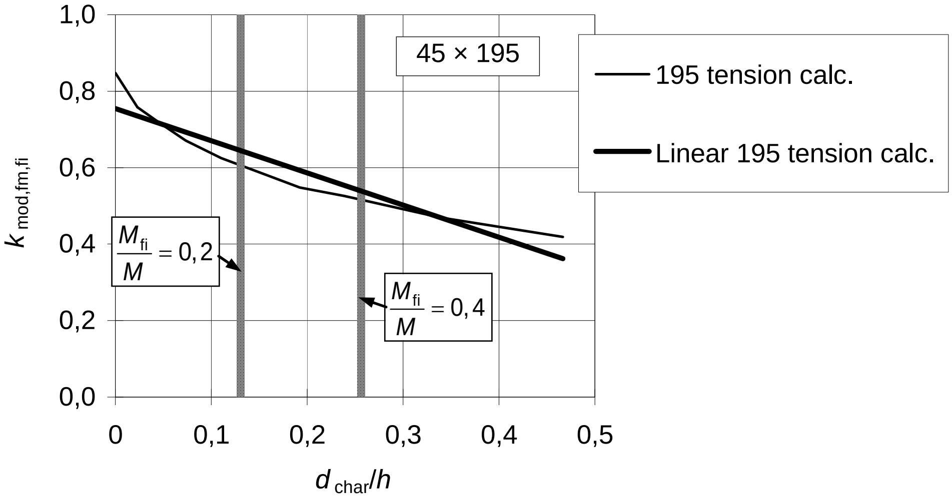


Figure 2.2 – Determination of simplified relationship of modification factor $k_{\mathrm{mod,fm,fi}}$ versus relative charring depth for a cross-section of 45 mm × 195 mm [2].

Using the background data of [2], for each of the cross-sections with widths b of 38, 45 and 60 mm and depths h of 95, 145, 195 and 220 mm the relationship of bending resistance ratio M_{fi}/M versus relative charring depth d_{char}/h were calculated and plotted in Figure 2.3 to 2.4. In the calculations it was assumed that either the tensile or compressive side was exposed to fire. The temperature in the timber member was calculated under the assumption that the fire protective gypsum plasterboard cladding remained in place after the start of charring. In such scenario, the rate of heat transfer is slower, the temperature gradient in the timber member is smaller and therefore the reduction of strength and stiffness is greater compared to the case of unprotected timber members. For the stage after failure of the cladding, the assumption made is conservative.

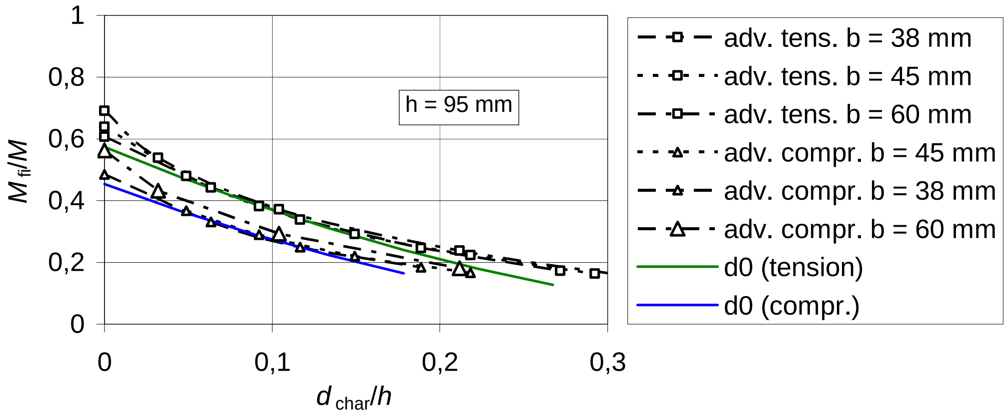


Figure 2.3 – Moment resistance ratios versus relative charring depth according to advanced calculations and reduced cross-section method.

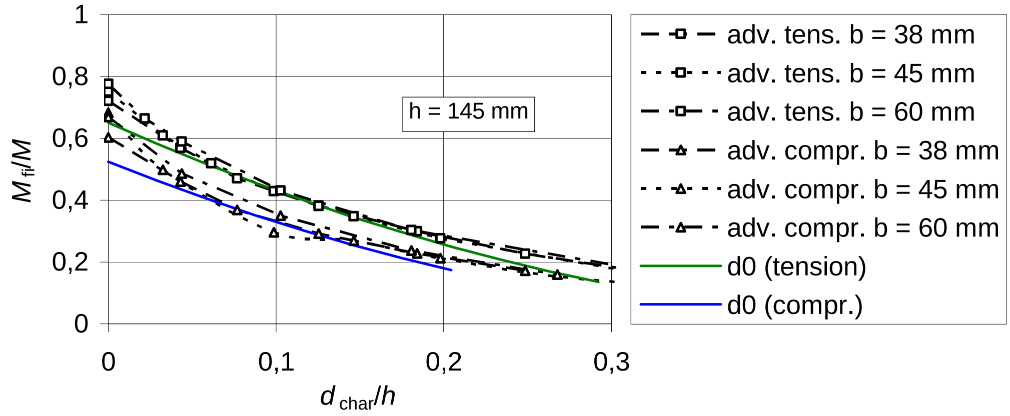


Figure 2.4 – Moment resistance ratios versus relative charring depth according to advanced calculations and reduced cross-section method.

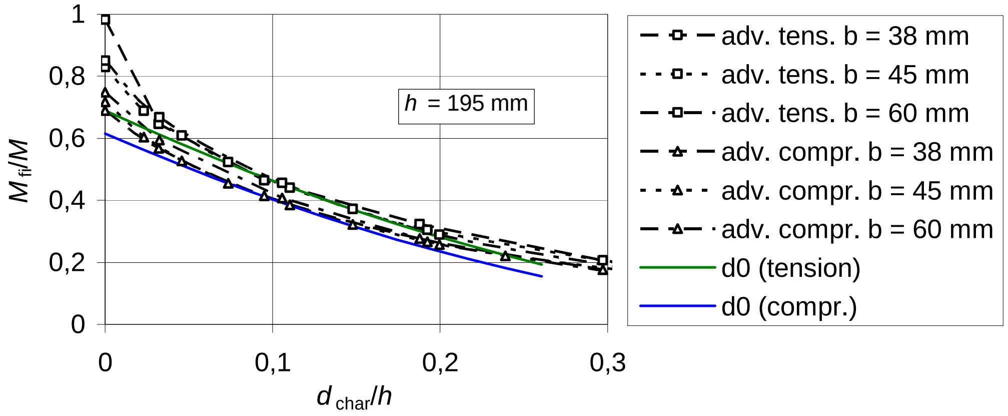


Figure 2.5 – Moment resistance ratios versus relative charring depth according to advanced calculations and reduced cross-section method.

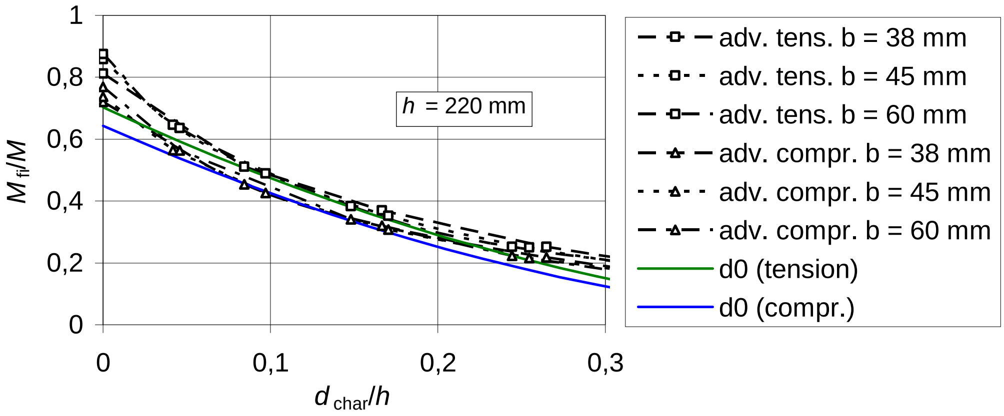


Figure 2.6 – Moment resistance ratios versus relative charring depth according to advanced calculations and reduced cross-section method.

By trial and error, zero-strength layers d_0 (see Figure 2.1) were determined such that the corresponding moment resistance ratio curves gave the best fit for load resistance ratios between 0,2 and 0,4. In these calculations, the charring depth was replaced by the notional charring depth according to expressions (1.4) and (1.5). Since the influence of the width b is small, the zero-strength layer d_0 can be expressed as a function of depth h:

– For members with the fire exposed side in tension

$$d_0 = 13{,}5 + \frac{h}{10} \tag{2.2}$$

– For members with the fire exposed side in compression

$$d_0 = 21{,}5 + \frac{h}{10} \tag{2.3}$$

For members with the fire exposed side in tension, for cross-section depths between 95 and 220 mm, d_0 varies from 23 to 35,5 mm, while it is further 8 mm greater when the fire exposed side is in compression.

2.3 Axially loaded members (wall studs)

For axially loaded members column buckling is the relevant failure mode and therefore bending stiffness EI is the most relevant design parameter. Therefore, for the cross-sections studied in [2], relationships of the relative bending stiffness $\frac{(EI)_{\mathrm{fi}}}{EI}$ versus the charring ratio $\frac{d_{\mathrm{char}}}{h}$ were determined for the following cases (for the definition of the y and z-axis see Figure 2.7):

- Fire exposure on one side for deflection in the z-direction (Figure 2.8 to 2.9)
- Fire exposure on one side for deflection in the y-direction (Figure 2.11 to 2.12)
- Fire exposure on two sides for deflection in the z-direction (Figure 2.14)
- Fire exposure on two sides for deflection in the y-direction (Figure 2.15).

In these calculations, the linear expressions for the modification factors $k_{\mathrm{mod,E,fi}}$, derived from advanced calculations in [2], were used.

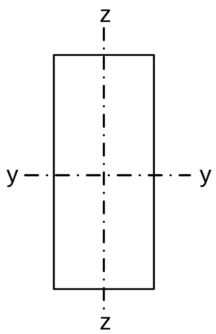


Figure 2.7 – Definition of axes.

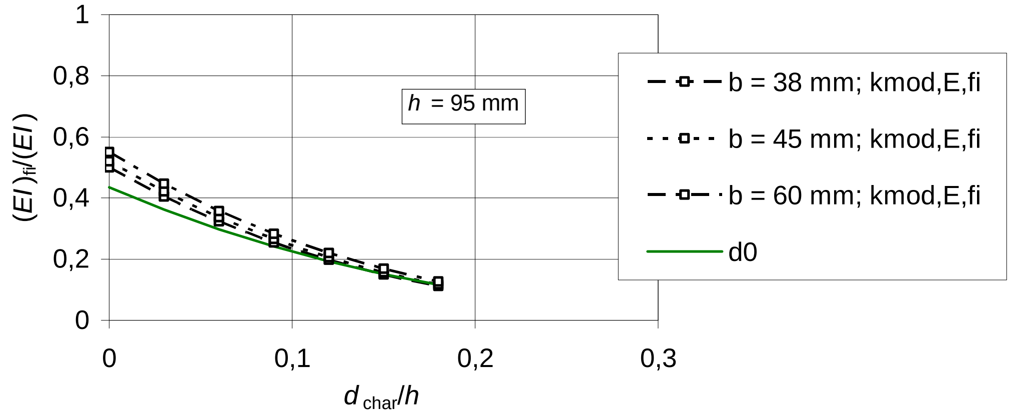


Figure 2.8 – Comparison of relative bending stiffness versus relative charring for deflection in z-direction.

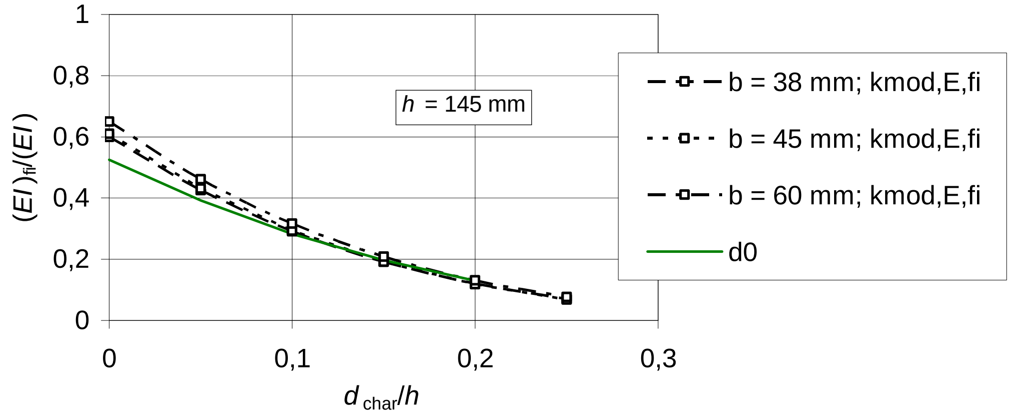


Figure 2.9 – Comparison of relative bending stiffness versus relative charring for deflection in z-direction.

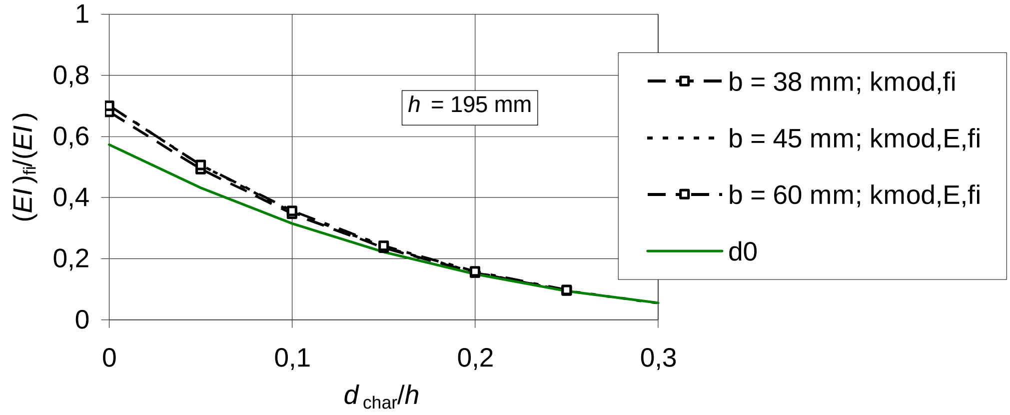


Figure 2.10 – Comparison of relative bending stiffness versus relative charring for deflection in z-direction.

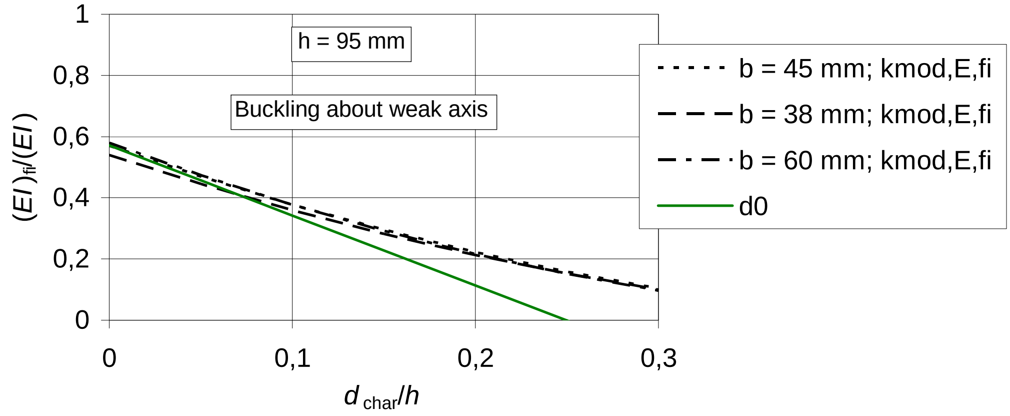


Figure 2.11 – Comparison of relative bending stiffness versus relative charring for deflection in y-direction.

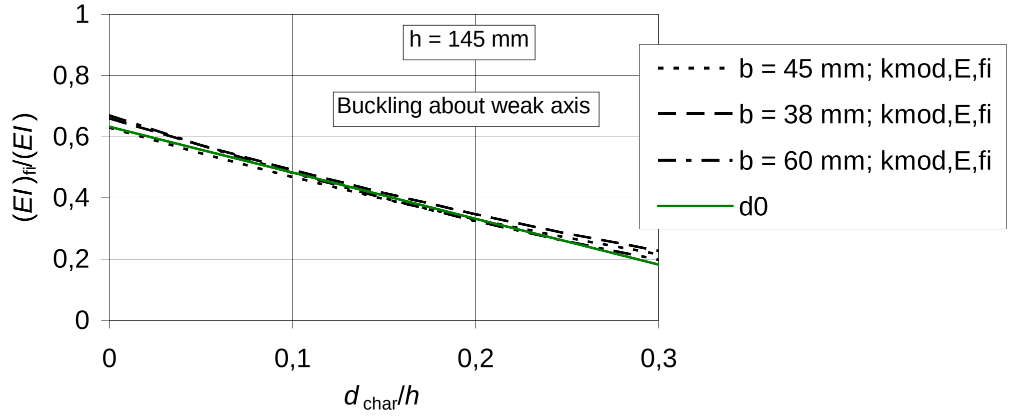


Figure 2.12 – Comparison of relative bending stiffness versus relative charring for deflection in y-direction.

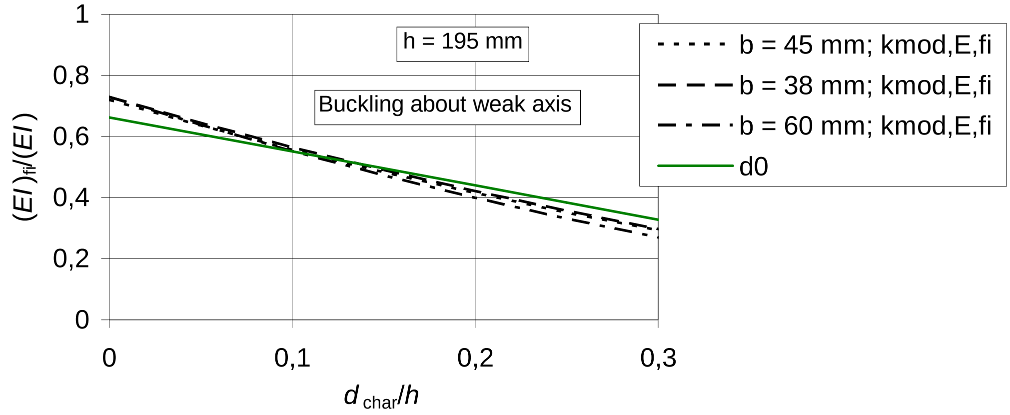


Figure 2.13 – Comparison of relative bending stiffness versus relative charring for deflection in y-direction.

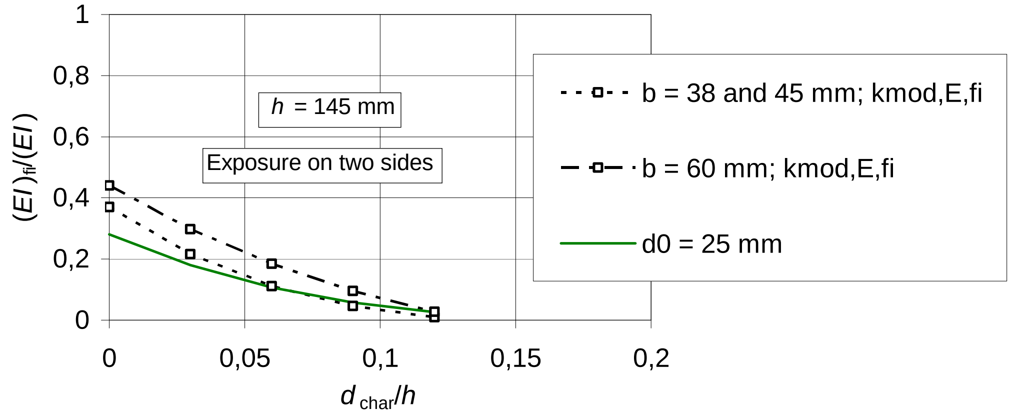


Figure 2.14 – Comparison of relative bending stiffness versus relative charring for deflection in z-direction and fire exposure on both sides.

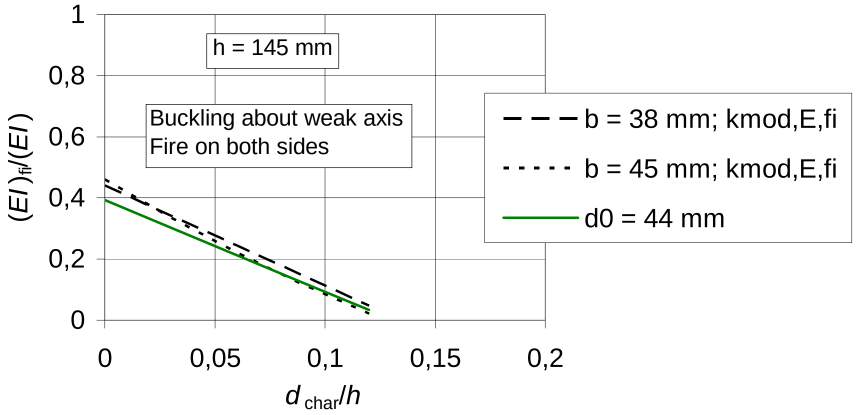


Figure 2.15 – Comparison of relative bending stiffness versus relative charring for deflection in y-direction and fire exposure on both sides.

Calculating the relative bending stiffness using an effective cross-section, the following expressions and values give reasonable agreement with the curves obtained from $k_{\mathrm{mod,fi}}$-values:

- For fire exposure on one side for deflection in the z-direction (relevant for buckling about the y-axis perpendicular to the wall):

  $$d_0 = 13{,}5 + \frac{h}{10} \tag{2.4}$$

  (the same as expression (2.2))
- For fire exposure on one side for deflection in the y-direction (relevant for buckling about the z-axis parallel to the wall):

  $$d_0 = 17 + \frac{h}{4} \tag{2.5}$$
- For fire exposure on both sides for deflection in the z-direction (relevant for buckling about the y-axis perpendicular to the wall):

  $$d_0 = 25\ \mathrm{mm} \tag{2.6}$$
- For fire exposure on one side for deflection in the y-direction (relevant for buckling about the z-axis parallel to the wall):

  $$d_0 = 44\ \mathrm{mm} \tag{2.7}$$

2.4 Comparison with reduced properties method

2.4.1 Members in edgewise bending

For two cross-sections, 45 mm × 145 mm and 45 mm × 195 mm, the relationships of relative bending moment resistance versus relative charring depth are shown for members with fire exposure on the tension side, see Figure 2.16 and 2.17. It can be seen that the linear model for $k_{\mathrm{mod,fm,fi}}$ gives moment resistance values that are slightly non-conservative for relative resistance values greater than 0,2. The values calculated using a zero-strength layer agree well with the non-linear model for $k_{\mathrm{mod,fm,fi}}$.

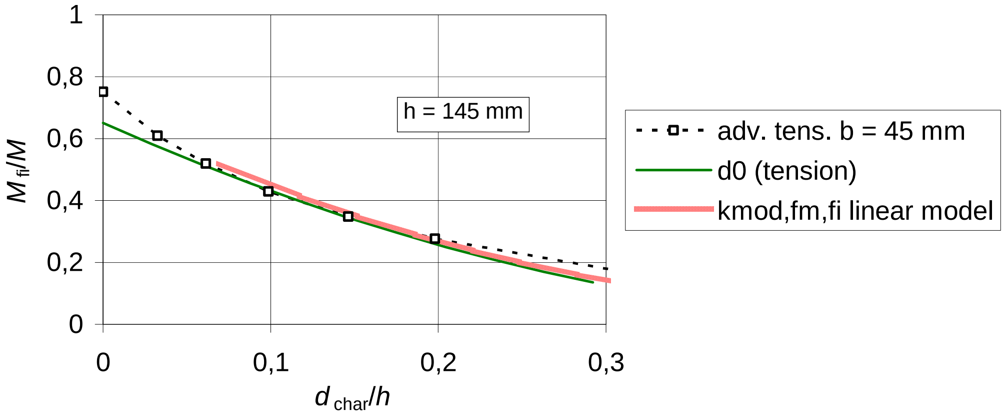


Figure 2.16 – Comparison of models

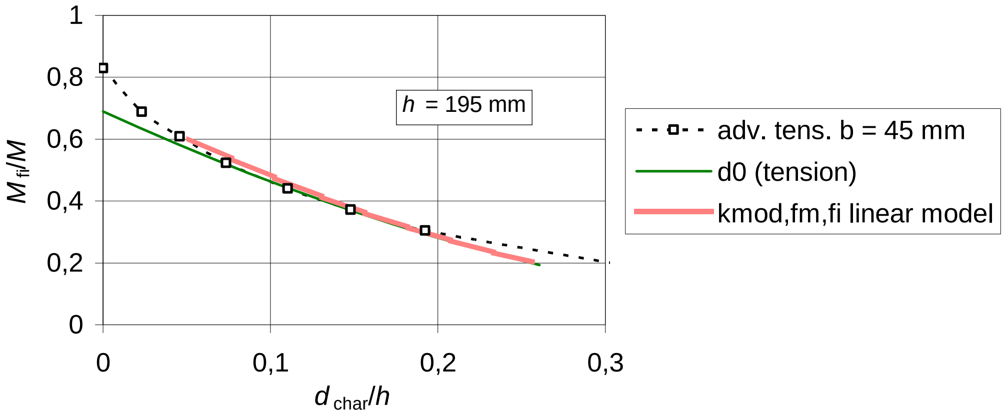


Figure 2.17 – Comparison of models

2.4.2 Axially loaded members

Verification of mechanical resistance in fire means, in terms of EN 1995-1-2 [1], that the design method or model is the same as for the design at ambient temperature, however with material and cross-section properties that are relevant for the fire exposed members. Applying the reduced properties method to axially loaded members, different modification factors for fire are applied to modulus of elasticity and compressive strength. As an approximation, the modification factor for compressive strength was replaced by the modification factor for bending strength, $k_{mod,fm,fi}$ when the fire exposed side of the member is in compression. This approximation is justified since the calculated axial resistance is only slightly sensitive to variations of $k_{mod,fm,fi}$. Since the reduced cross-section method cannot assume different zero-strength layers for the same member, the most relevant value of d_0 relevant for bending stiffness was used.

Figure 2.18 shows a comparison of both methods, carried out for a timber stud of size 45 mm × 145 mm protected by gypsum plasterboards which remain in place during the fire. The axial resistance was calculated according to EN 1995-1-1 [3] with the relevant model parameters taking into account the effect of charring and reduced strength and stiffness properties. The axial resistance calculated using the effective cross-section method is between 2,5 and 10 % larger for relative resistance values between 0,4 and 0,2.

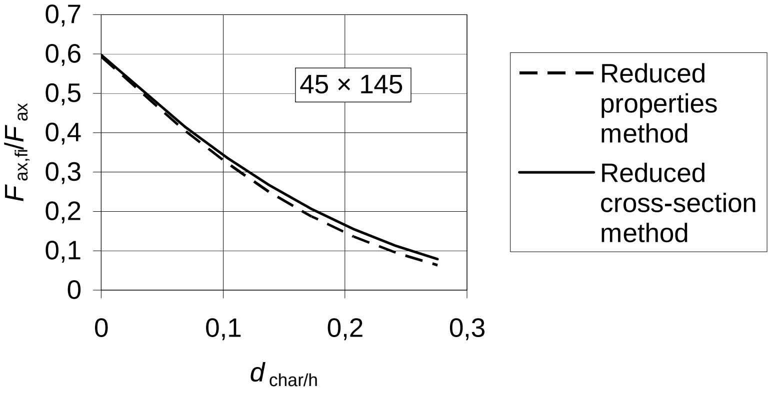


Figure 2.18 – Comparison of models: Timber stud protected by gypsum plasterboard

2.4.3 Conclusions

It has been shown that the reduced properties method for the calculation of the mechanical resistance of timber frame members (studs or joists) in wall and floor assemblies can be replaced by the reduced cross-section method using zero-strength layers instead of modification factors for fire. This will simplify design work. For members in bending, the bending resistance according to the reduced cross-section agrees well with results from the reduced properties method since the zero-strength layers were determined to achieve the best fit for load ratios in the range between 0,2 and 0,4 which is most important in practice. Only for load ratios smaller than 0,2 the results are slightly non-conservative. For axially loaded members the calculated resistance is somewhat greater according to the reduced cross-section method when the method for axially loaded members given in EN 1995-1-1 [3] is used, however with properties relevant for the fire situation. Since the zero-strength layer is equivalent to the modification factors for fire, the difference between the calculated axial resistances is mainly due to the different weighting of parameters (such as slenderness ratios, relative slenderness ratios, area, etc.) in the expressions given in EN 1995-1-1.

3 References

[1] EN 1995-1-2:2004 Eurocode 5: Design of timber structures – Part 1-2: General – Structural fire design. European Standard. European Committee for Standardization, Brussels, 2004.

[2] König, J, Timber frame assemblies exposed to standard and parametric fires. Part 2: A design model for standard fire exposure. Trätek, Swedish Institute for Wood Technology Research, Report nr 0001001, Stockholm, 2000.

[3] EN 1995-1-1:2004 Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings. European Standard. European Committee for Standardization, Brussels, 2004.

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