TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Civil Engineering and Architecture

EVALUATION OF PROPOSED CHANGES TO THE FIRE DESIGN MODELS FOR LINEAR GLULAM MEMBERS IN EUROCODE 5

EUROKOODEKS 5 LIIMPUIDUST VARRASELEMENTIDE TULEPÜSIVUSE ARVUTUSMEETODITES KAVANDATUD MUUDATUSTE HINDAMINE

MASTER THESIS

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Student code: 153961EAEI

Supervisor: Professor Alar Just

Tallinn 2021

AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.
No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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Department of Civil Engineering and Architecture

THESIS TASK

Student: Mariliis Reineberg, 153961EAEI
Study programme: EAEI02/15 Design of buildings
Supervisor(s): Prof. Alar Just

Thesis topic:

Evaluation of proposed changes to the fire design models for linear glulam members in the Eurocode 5

Thesis main objectives:

1. To perform calculations of load bearing capacities of selected linear glulam members according to EN 1995-1-2:2004 and 3rd Draft of EN 1995-1-2:2020.
2. To compare described design methods and evaluate the changes.
3. Compare calculation results and test results.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Selection of structures and parameters for evaluation	1.4.2020
2.	Calculations of glulam members according to existing and new design methods	1.6.2020
3.	Comparison of design methods	1.10.2020
4.	Comparison with test results	1.11.2020
5.	Finalizing the work	6.1.2021

Language: English **Deadline for submission of thesis:** 7th January 2021

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TTÜ Ehituse ja arhitektuuri instituut

LÕPUTÖÖ ÜLESANNE

Üliõpilane: Mariliis Reineberg, 153961EAEI

Õppekava, peaeriala: EAEI02/15 – Ehitiste projekteerimine ja ehitusjuhtimine

Juhendaja: Professor Alar Just

Lõputöö teema:

Eurokoodeks 5 liimpuidust varraselementide tulepüsivuse arvutusmeetodites kavandatud muudatuste hindamine

Evaluation of proposed changes to the fire design models for linear glulam members in the Eurocode 5

Lõputöö põhieesmärgid:

1. Teostada valitud puitkonstruktsioonide tulepüsivusarvutused EN1995-1-2:2004 ning sama standardi uue versiooni kavandi arvutusmeetodite järgi.
2. Võrrelda tulepüsivuse arvutusmeetodeid ning hinnata muutusi võrreldes olemasolevaga.

Lõputöö etapid ja ajakava:

Nr	Ülesande kirjeldus	Tähtaeg
1.	Hinnatavate konstruktsioonide ja parameetrite valik	1.4.2020
2.	Liimpuitkonstruktsioonide arvutused EN 1995-1-2:2004 ja uute arvutusmeetodite järgi	1.6.2020
3.	Analüüs ja järeldused	1.10.2020
4.	Võrdlus katsetulemustega	1.11.2020
5.	Töö vormistamine	6.1.2021

Töö keel: inglise **Lõputöö esitamise tähtaeg:** “7” jaanuar 2021.a

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Juhendaja: **Alar Just** .... “.......”....................2021.a

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CONTENTS

PREFACE

I take this opportunity to express my gratitude to everyone that has supported me through studies and thesis writing. Especially, I would like to thank my supervisor Alar Just for suggesting the topic of this thesis and for his guidance. His support and encouragement has been beyond my expectations.

I am thankful for my family and friends for supporting me through studies, especially Jane, Leena and Eliise.

In this thesis, fire resistances of glulam beams and columns are calculated according to EN 1995-1-2:2004 and EN 1995-1-2:2020. Results are compared to the test results. In addition, user experience of EN 1995-1-2:2004 and :2020 is evaluated.

Keywords: fire resistance, glulam, Eurocode 5, linear member

List of abbreviations and symbols

Latin upper case letters

A	the area of effective cross-section
$E_{0,05}$	the fifth percentile value of the modulus of elasticity parallel to the grain
$E_{d,fi}$	design effect of actions for the fire situation
F	applied force
GtA	gypsum plasterboard type A
GtF	gypsum plasterboard type F
I_y	the moment of inertia
M	the bending moment
$M_{max,fi}$	maximum bending moment in fire situation
N	the compressive stress
$N_{max,fi}$	maximum compressive force in fire situation
$R_{d,t,fi}$	design resistance in the fire situation
W_{ef}	second modulus of effective cross-section

Latin lower case letters

b	width of the initial cross-section
b_{ef}	effective width of the effective cross-section
d_0	zero-strength layer depth
$d_{char,n}$	notional charring depth
d_{ef}	effective charring depth
e	eccentricity
f_{20}	the 20% fractile of a strength property at normal temperature
$f_{c,0,d}$	the design compressive strength along the grain
$f_{c,0,k}$	the compressive strength along the grain
$f_{d,fi}$	design strength in fire
f_k	characteristic strength
$f_{m,y,d}$	design bending strength about the principal y-axis
$f_{m,z,d}$	design bending strength about the principal z-axis
h	height of the initial cross-section
h_{ef}	effective height of the effective cross-section
h_p	thickness of protective panel

i_y	the radius of gyration
k_0	coefficient
k_2	protection factor
k_3	post-protection factor
k_4	consolidation factor
$k_{c,y}$	the instability factor
k_{fi}	modification factor for a strength or stiffness property for the fire situation
k_{gd}	modification factor considering grain direction
k_i	modification factors
$k_{j,i}$	joint coefficient for layer i
k_m	factor considering re-distribution of bending of stresses in apex zone
$k_{mod,fi}$	modification factor for fire
k_n	conversion factor
$k_{pos,exp,i}$	position coefficient that takes into account the influence of layers preceding the layer considered
$k_{pos,unexp,i}$	position coefficient that takes into account the influence of layers backing the layer considered
k_{sides}	number of respective sides exposed to fire
k_y	the instability factor
k_Θ	temperature-dependent reduction factor for a strength or stiffness property
l_{ef}	the effective length of member
t	time of fire exposure
t_a	Time to reach the consolidated charring phase;
t_{ch}	Start time of charring;
t_f	Failure time of the fire protection system, in min.
$t_{f,pr}$	Failure time of the fire protection system, in min.
$t_{prot,0,i}$	basic protection time of the considered layer i
t_{prot}	protection time of each layer i in the heat flux

Greek upper case letters

Xd,fi	Design value of a strength or stiffness property for fire temperature design
Xk	normal temperature design
Δti	correction time for the considered layer i
Σtprot	sum of protection time

Greek lower case letters

β_0	basic design charring rate
β_n	notional charring rate within one charring phase
$\beta_{n,Phase2}$	notional charring rate during the protection phase (phase 2)
$\beta_{n,Phase3}$	notional charring rate during the protection phase (phase 3)
$\beta_{n,Phase4}$	notional charring rate during the protection phase (phase 4)
$\gamma_{M,fi}$	partial factor for the relevant mechanical material property for the fire situation
$\lambda_{rel,y}$	the relative slenderness ratio
λ_y	slenderness ratio corresponding to bending about the y-axis
μ	the support factor
$\sigma_{c,0,d}$	the design compressive stress along the grain
$\sigma_{m,y,d}$	design bending stress about the principal y-axis
$\sigma_{m,z,d}$	design bending stress about the principal z-axis

1. INTRODUCTION

Timber has been used as a construction material for centuries. However, many regulations and standards restrict the use of timber in construction due to the combustibility of timber [1]. European countries have different limitations for the number of storeys permitted in load bearing structures as can be seen in Figure 1.1.

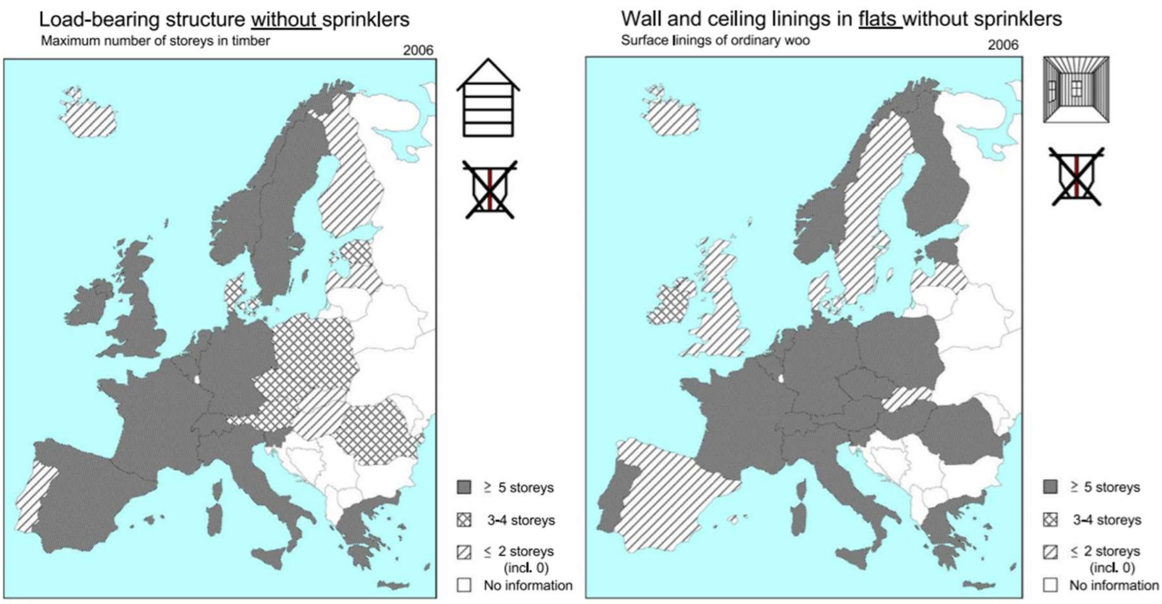


Figure 1.1 Restricted use of load-bearing timber structures and visible wood set by national prescriptive regulations [2]

An important prerequisite in the more extensive use of timber in construction is adequate fire safety. Numerous research projects have been conducted and fire tests have been performed to collect data and information. According to the collected data, novel fire design models have been developed [1]. The improvements in the fire design models have led to the new version of Eurocode 5 part 1-2.

In this thesis, the fire resistance of glulam beams and columns are calculated according to EN 1995-1-2:2004 and EN 1995-1-2:2020. The results are compared to the test results. In addition, the user experiences of EN 1995-1-2:2004 and :2020 are evaluated. The examined beams and columns are shown in Figure 1.2 and Figure 1.3. 4 cross-sections were chosen for beams and 3 for columns. All the members were examined with 3 different protective layers: no protective layer, one layer of GtA 12,5 and one layer of GtF 15. The types of gypsum plasterboards are specified in EN 520+A1:2010 [3]. Fire resistance after 30, 60 and 90 minutes was calculated for all the different combinations of members and protective layers.

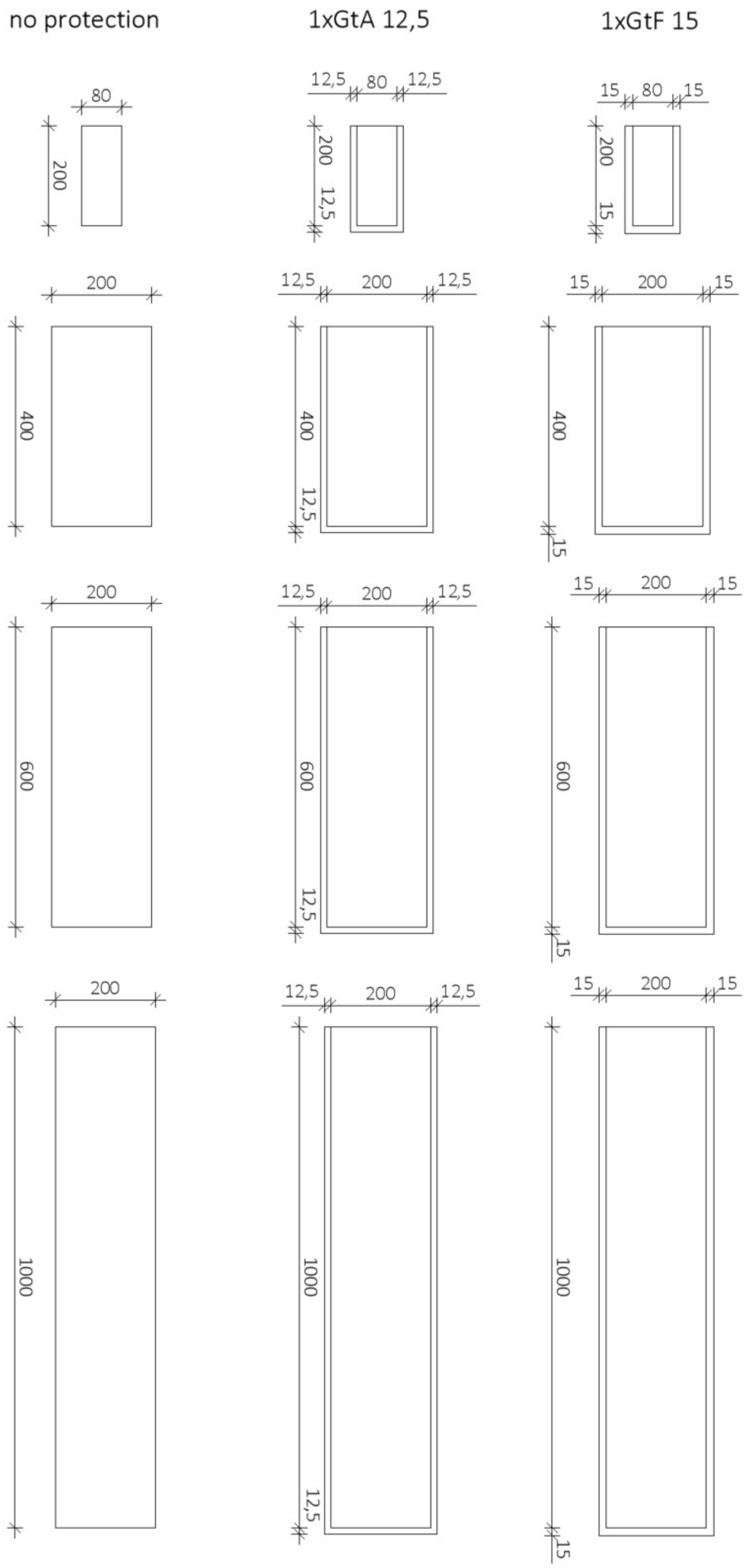


Figure 1.2 Cross-sections of beams used in this thesis

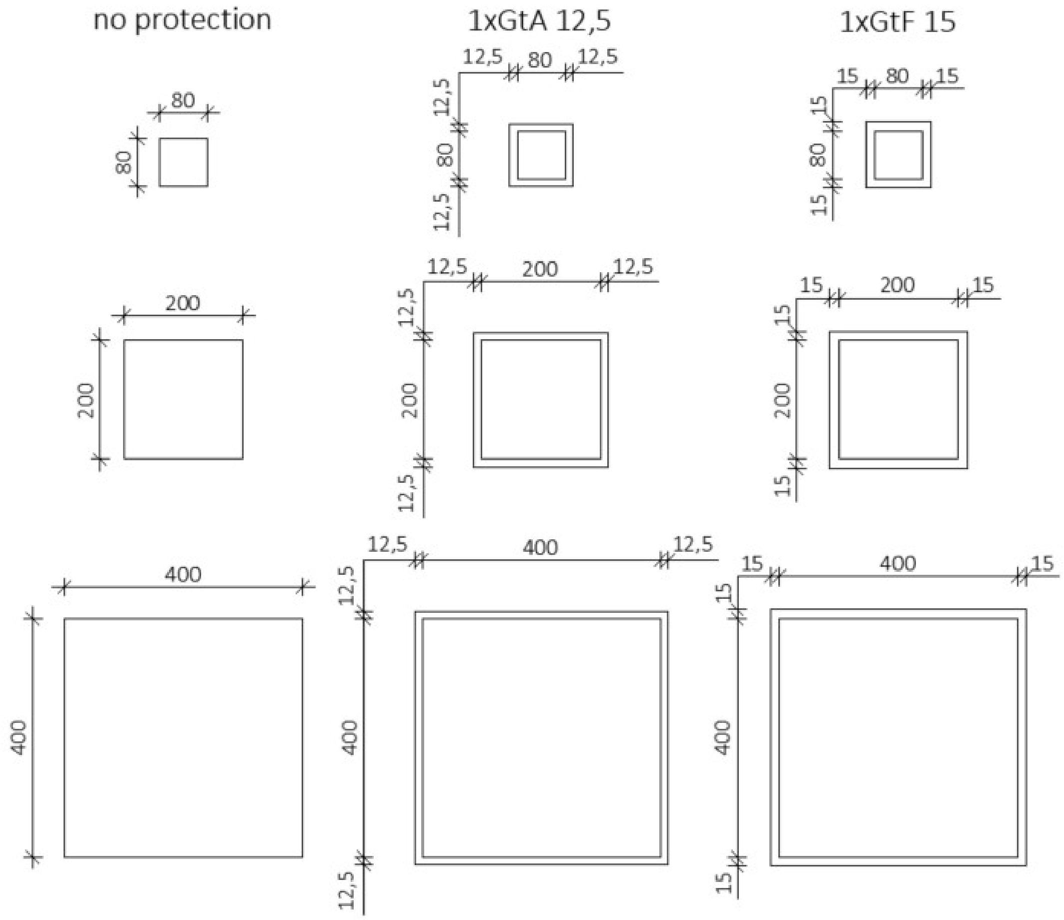


Figure 1.3 Cross-sections of columns used in this thesis

The topic was suggested by Alar Just. As this thesis was written during the revision of Eurocode 5 part 1-2, the results of the thesis can be used as feedback for the revision. This research presents how the proposed changes in Eurocode 5 part 1-2 affect the calculations of glulam beams and columns. The comparison with the test results evaluates whether the proposed changes give more realistic results than EN 1995-1-2:2004. The evaluation of user experience can be an useful information for the Project Team 4 of CEN TC250 SC5 and helps determine whether improvements could be added to EN 1995-1-2:2020.

In this thesis, the reduced cross-section method is used to evaluate fire resistance. A reduced cross-section is an initial cross-section without an effective char layer that, in addition to the char layer, considers the layer beneath it with reduced stiffness and strength properties [4]. A working platform has been created in Excel for calculations.

The main body of this thesis consists of two larger parts: an overview of the calculation methods and analysis.

Chapters 2-5 give an overview of the calculation methods. Chapter 2 covers the revision of the Eurocode 5 part 1-2. Chapters 3 and 4 elaborate on the calculation methods according to EN 1995-1-2:2004 and EN 1995-1-2:2020, respectively. Chapter 5 consists of the formulas used in this thesis from sources other than Eurocode 5 part 1-2.

The analysis consists of 3 parts: analysis of the calculation results, comparison with test results and user experience. Chapter 6 gives an analysis of the calculations. It covers the differences in calculation methods among EN 1995-1-2:2004 and EN 1995-1-2:2020 and the results of the calculations of the examined beams and columns that are shown in Figure 1.2 and Figure 1.3. Chapter 7 consists of a comparison of test results and calculations. Unfortunately, only limited data is available for compressed members in fire [5]. Therefore, the examined column (confidential), is in the Appendix 17 and Chapter 7 consists only of a comparison with beams. Chapter 8 evaluates the user experience according to the improvements and deficiencies of the user experience in EN 1995-1-2:2020.

This thesis includes 17 Appendices. Appendices 1-14 include calculation examples and the calculations of the results of all the examined members. Appendices 1-7 give calculations according to EN 1995-1-2:2004 and appendices 8-14 include calculations according to EN 1995-1-2:2020. Appendix 15 consists of calculations with the parameters of the tested beams and Appendix 16 gives an interview with Alar Just. Appendix 17 is a confidential comparison with a tested beam (including calculations) that is omitted from the published version.

2. REVISION OF EUROCODE 5 PART 1-2

Revision process and proposed changes are described in this chapter. Grate amount of information in this chapter is based on the interview with Alar Just, presented in Appendix 16.

Revision of Eurocode 5 Part 1-2

The revision of Eurocode 5 began in 2012. The background research for the revised fire part of Eurocode 5 (EN 1995-1-2) was collected and discussed at CEN TC250 SC5 WG4 (Fire). The revised fire part of Eurocode 5 has been drafted by Project Team 4 of CEN TC250 SC5 (Andrea Frangi, Alar Just, Jouni Hakkarainen, Norman Werther, Joachim Schmid).

The first draft of the revised EN 1995-1-2 was published in May 2019. The second draft was published in May 2020 followed by the third draft in October 2020. The third draft of EN 1995-1-2 is the basis of this master thesis. The Final version of the EN 1995-1-2 is delivered by the Project Team in May 2021. Subsequent to this, the balloting, commenting, technical review and synchronising with other parts of Eurocodes will follow. The publishing of the revised Eurocode 5 Part 1-2 is expected in 2025.

Hereafter the currently valid Eurocode 5 Part 1-2 is referred to as **EN 1995-1-2:2004** and the proposal for the revised Eurocode 5 Part 1-2 as **EN 1995-1-2:2020** (dated 30.10.2020).

Revision of the design models

In EN 1995-1-2:2004, the European Charring Model is used for charring calculations. There are no significant changes in the charring rate values. However, the terms and symbols are slightly changed. In EN 1995-1-2:2020, the basic design charring rates are given in Table 5.2. The notional design charring rate is calculated by taking the relevant influencing coefficients into account [6].

The European Charring Model consists of different charring phases as follows [6]:

- **normal charring phase (Phase 1**) for initially unprotected sides of timber members and for initially protected sides of timber members,
- **encapsulated phase (Phase 0)** is the phase when no charring occurs,
- **protected charring phase (Phase 2)** is the phase when charring occurs behind the protection while the system is still in place,

- **post-protected charring phase (Phase 3)** is the phase after failure of the protection before a fully developed char layer has been formed,
- **consolidated charring phase (Phase 4)** is the phase with a fully developed char layer.

For the protected timber members there are time limits between the phases defined. For the calculation of start time of charring the Separating Function Method from EN 1995-1-2:2020 is used [6]. The design values for start time of charring are slightly different compared to EN 1995-1-2:2004.

EN 1995-1-2:2020 contains the generic failure times of gypsum boards, Type F [6]. These failure times are not included in EN 1995-1-2:2004. The thesis includes failure times from Fire Safety in Timber Buildings (2010) when using the design model of EN 1995-1-2:2004.

Calculation of the consolidation time is similar for EN 1995-1-2:2004 and EN 1995-1-2:2020.

For the charring of glulam members, the bondline integrity is assumed to be maintained.

In EN 1995-1-2:2004, the load-bearing capacity of glulam members can be calculated by using the Reduced Properties Method or the Effective Cross-Section Method (previously called the Reduced Cross-Section Method). In the revision process, TC250 SC5 WG4 made a decision that only the Effective Cross-section Method will be included in the revised version of EN 1995-1-2:2020. The Reduced Properties Method has not been further improved.

Many studies have shown that the load bearing capacity of the linear timber members in fire, calculated according to EN 1995-1-2:2004, can deliver overestimated fire resistance [7] [8]. The zero-strength layer of 7 mm according to EN 1995-1-2:2004 is not sufficient to compensate the stress loss of heated timber. The zero-strength layer values proposed in EN 1995-1-2:2020 are increased compared to EN 1995-1-2:2004.

3. DESIGN ACCORDING TO EN 1995-1-2:2004

Main parameters for design of glulam members in fire according to EN 1995-1-2:2004 are described in the following chapters.

3.1 Strength of timber in fire

The strength of timber is not constant in all conditions. The design strength of timber in fire is also different from the design strength of timber under normal temperatures [9]. The design value of the strength of material in case of fire should be calculated according to formula (3.1) [10].

$$\mathrm{f_{d,fi}} = \mathrm{k_{mod,fi}} \frac{\mathrm{f_{20}}}{\mathrm{\gamma_{M,fi}}}, \tag{3.1}$$

where $f_{d,fi}$ – design strength in fire, N/mm²,

$k_{mod,fi}$ – modification factor for fire,

f_{20} – the 20% fractile of a strength property at normal temperature, N/mm²,

$\gamma_{M,fi}$ – the partial safety factor for timber in fire.

It is recommended, that $\gamma_{M,fi}$ = 1,0, unless a different value is given in the National Annex [10]. As the calculations are based on an effective cross-section method, the modification factor for fire is $k_{mod,fi}$ = 1,0 [10]. The 20% fractile of strength property at normal temperature f_{20} is calculated according to formula (3.2) [10].

$$f_{20} = k_{fi} f_k, \tag{3.2}$$

where k_{fi} – coefficient,

f_k – characteristic strength, N/mm².

The value of coefficient k_{fi} for glue-laminated timber is 1,15 [10]. The characteristic strength of glue-laminated timber is taken from European standard EN 14080:2013 [11].

3.2 Charring depth of initially unprotected member

As the initially unprotected members are exposed to fire from the beginning of the fire, the charring process also starts with the fire. The charring rate for initially unprotected members is constant throughout the fire exposure [10]. See Figure 3.1.

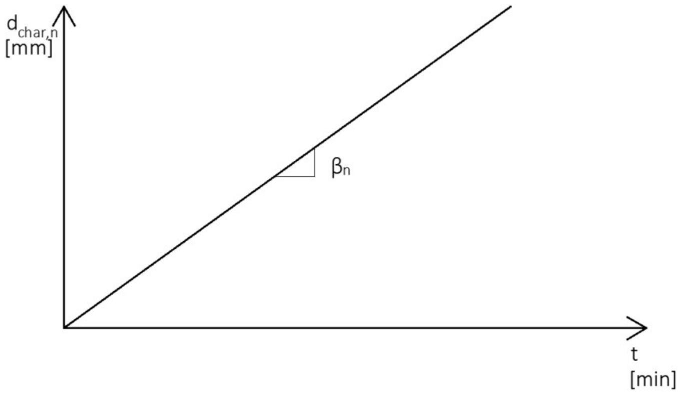


Figure 3.1 Relationship for initially unprotected members throughout the time of fire exposure [10]

In this research, all members are exposed to fire from more than 2 sides. Consequently, the notional charring rate should be taken into consideration. The notional charring rate includes the effect of corner roundings and fissures. It is calculated according to formula (3.3) [10]

$$d_{char,n} = \beta_n t, \tag{3.3}$$

where $d_{char,n}$ – notional charring depth, mm,

β_n – notional charring rate, mm/min

t − time of fire exposure, min.

The notional charring rate β_n for glued laminated timber with a characteristic density of ≥ 290 kg/m^3 is 0,7 mm/min. The permission of 3.4.2 (3) is not applied in this thesis [10].

3.3 Charring depth of initially protected member

If the timber member is protected from direct fire exposure, the start of charring is delayed until time t_{ch}. Other important moments for the charring of initially protected members are the failure of protection t_f and time limit t_a [10]. For calculation of t_{ch} see 3.3.2, for calculation of t_f see 3.3.3 and for t_a see 3.3.4.

3.3.1 Variations of charring depth with time for initially protected member

The charring of initially protected members has different variations. Those variations are presented in Figure 3.2, Figure 3.3 and Figure 3.4.

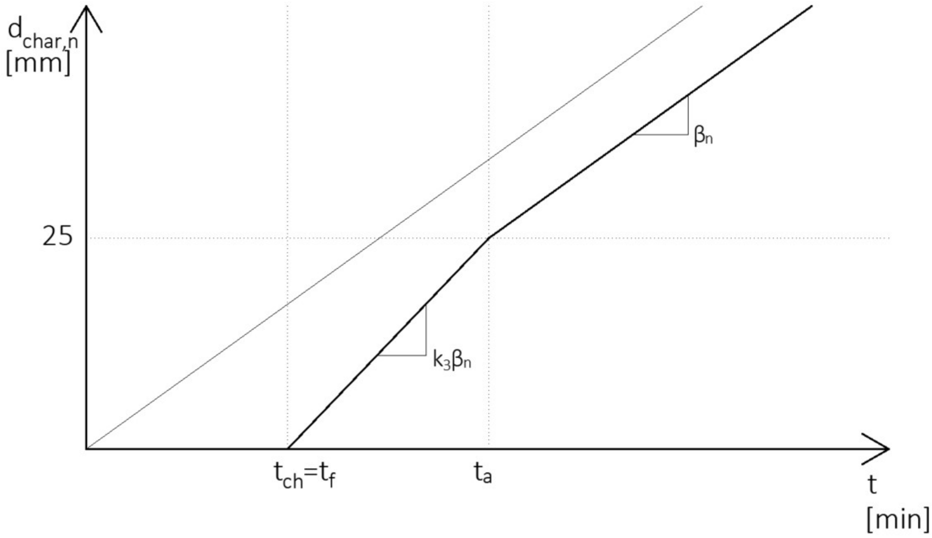


Figure 3.2 Determination of charring depth with time when t_{ch}=t_f and the charring depth at time t_a is at least 25 mm. Reference line is charring of initially unprotected member. [10]

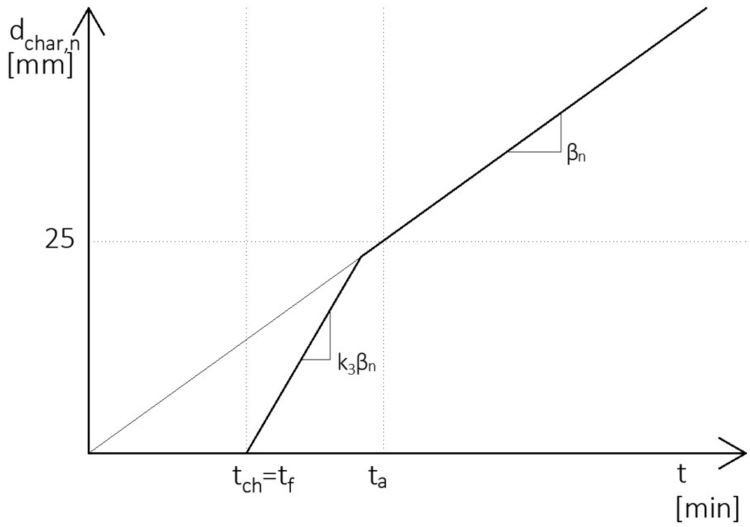


Figure 3.3 Determination of charring depth with time when t_{ch}=t_f and the charring depth at time t_a is less than 25 mm. Reference line is charring of initially unprotected member. [10]

As seen in figures 3.2 and 3.3, an initially protected member that has the start time of charring equal with the failure time of protection, has 2 different charring rates. Between t_{ch} and t_a the member chars at a higher rate. The notional charring rate β_n is multiplied by a factor $k_3 = 2$. After t_a the member chars at the same rate as the initially unprotected member, which in this research is 0,7 mm/min [10].

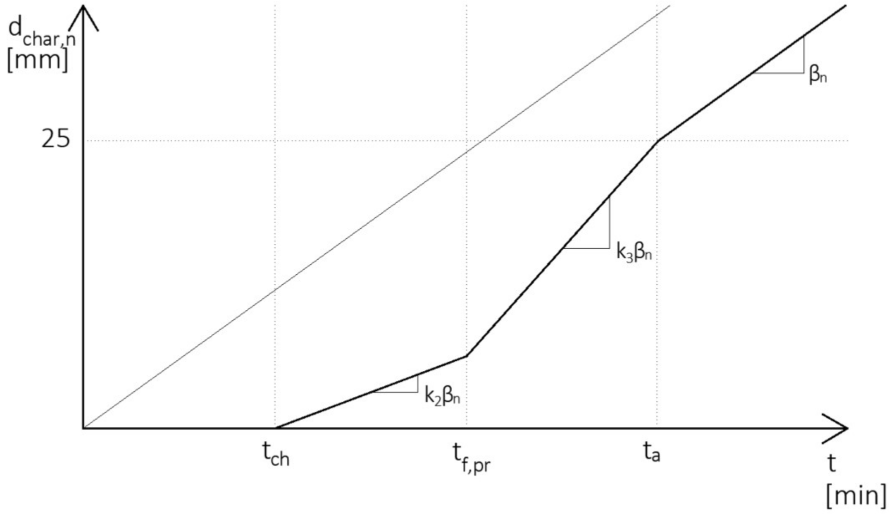


Figure 3.4 Determination of charring depth with time when t_{ch}<t_{f}. Reference line is charring of initially unprotected member. [10]

If $t_{ch} < t_f$, between t_{ch} and t_f, the member chars at a lower rate. Then the notional charring rate β_n is multiplied by a factor k_2. For gypsum plasterboard type F, k_2 should be calculated using formula (3.4) [10].

$$k_2 = 1 - 0{,}018 h_p, \tag{3.4}$$

where h_p – thickness of protective layer, mm.

After t_f, charring occurs similarly to members with $t_{ch} = t_f$ [10].

3.3.2 Start time of charring of protective layer

In this research, the protective layer consists of one layer of gypsum plasterboard type A or F. For claddings made of one layer of gypsum plasterboard type A or F with unfilled joints with a width less than 2mm, the start of charring should be taken as in the equation (3.5) [10].

$$t_{ch} = 2{,}8\, h_p - 14 \tag{3.5}$$

where h_p – thickness of layer, mm.

3.3.3 Failure time of protective layer

The failure time of gypsum plasterboard type A should be calculated according to the formula (3.6) [10].

$$t_f = t_{ch} \tag{3.6}$$

The standard EN 1995-1-2:2004 does not give a value or equation for the failure time of gypsum plasterboard type F. In this research, the failure time of gypsum plasterboard type F is taken as equation (3.7) follows [12].

$$t_f = \begin{cases} 4{,}5h_p - 24, for\ columns \\ h_p + 10, for\ beams \end{cases} \tag{3.7}$$

3.3.4 The time limit t_a

The time limit t_a is the moment, when the depth of the char layer reaches 25 mm or the charring depth of the same member without fire protection [10].

If $t_{ch} = t_f$, the time t_a is calculated according to formula (3.8) [10].

$$t_a = \min \begin{cases} 2t_f \\ \dfrac{25}{k_3\beta_n} + t_f \end{cases} \tag{3.8}$$

where t_f – failure time of the fire protection, min,

k_3 – post-protection coefficient,

β_n – notional charring rate, mm/min.

If $t_{ch} < t_f$, time t_a is calculated according to formula (3.9) [10].

$$t_a = \frac{25 - (t_f - t_{ch})k_2\beta_n}{k_3\beta_n} + t_f \tag{3.9}$$

where t_f – failure time of the fire protection, min,

t_{ch} – start of charring, min,

k_3 – post-protection coefficient,

k_2 – insulation coefficient,

β_n – notional charring rate, mm/min.

3.4 Effective cross-section of the member

An effective cross-section of the member is an initial cross-section reduced by effective charring depth d_{ef} from all fire exposed sides. An effective cross-section is calculated using the formula (3.10) [10].

$$d_{ef} = d_{char,n} + k_0 d_0 \tag{3.10}$$

where d_0 – depth of zero-strength layer, mm,

k_0 – coefficient,

$d_{char,n}$ – notional charring depth, mm.

Value of the depth of zero-strength layer is 7 mm [10].

The coefficient k_0 is a variable coefficient. For unprotected members and initially protected members with the start of charring $t_{ch} < 20$ min, k_0 is calculated according to equation (3.11) [10].

$$k_0 = \begin{cases} \dfrac{t}{20} & \text{if t} < 20 \text{ min} \\ 1{,}0 & \text{if t} \geq 20 \text{ min} \end{cases} \tag{3.11}$$

For initially protected members with the start of charring $t_{ch} \geq 20$ min, k_0 is calculated according to formula (3.12) [10].

$$k_0 = \begin{cases} \dfrac{t}{t_{ch}} & \text{if t} < t_{ch} \text{ min} \\ 1{,}0 & \text{if t} \geq t_{ch} \text{ min} \end{cases} \tag{3.12}$$

The measurements of the effective cross-section are an effective height h_{ef} and an effective width b_{ef}. In this research, beams are open to fire from 3 sides. In that case, the measurements of the effective cross-section is shown in Figure 3.6 and is calculated according to formula (3.13) [10].

$$\begin{aligned} h_{ef} &= h - d_{ef} \\ b_{ef} &= b - 2d_{ef} \end{aligned} \tag{3.13}$$

where h_{ef} – effective height of cross-section, mm,

h – initial height of cross-section, mm,

b_{ef} – effective width of cross-section, mm,

b – initial width of cross-section, mm.

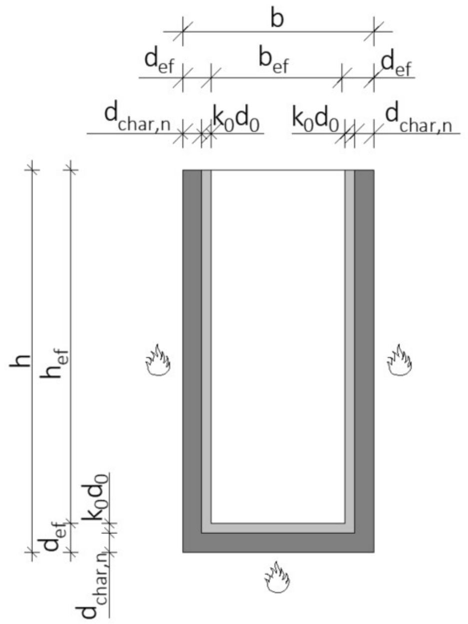


Figure 3.5 Effective cross-section for beams

In this research, columns are open to fire from 4 sides. In that case, the measurements of the effective cross-section is shown in Figure 3.6 and is calculated according to formula (3.14) [10].

$$h_{ef} = h - 2d_{ef}$$
$$b_{ef} = b - 2d_{ef} \quad (3.14)$$

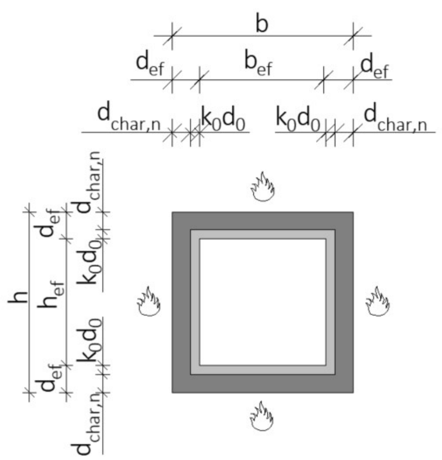


Figure 3.6 Effective cross-section for columns

4. DESIGN ACCORDING TO EN 1995-1-2:2020

Main parameters for design of glulam members in fire according to EN 1995-1-2:2004 are described in the following chapters.

4.1 Strength of timber in fire

In the 2020 version of Eurocode 5 the strength property for the fire situation is calculated according to formula (4.1) [6].

$$X_{d,fi} = \frac{k_{\Theta} k_{fi} X_{\mathrm{k}}}{\gamma_{M,fi}}, \tag{4.1}$$

where $X_{d,fi}$ – design value of strength property for the fire situation, N/mm^2,

k_{Θ} – temperature-dependent reduction factor for strength,

k_{fi} – modification factor for a strength property for the fire situation,

X_{k} – characteristic value of a strength property for normal temperature, N/mm^2,

$\gamma_{M,fi}$ – partial factor for the relevant mechanical material property for the fire situation.

The value of modification factor k_{fi} for glued laminated timber is 1,15 [6].

In this thesis, the maximum mechanical resistance at the required time is calculated. The design resistance has to satisfy the following condition (4.2) [6].

$$E_{d,fi} \leq R_{d,fi}, \tag{4.2}$$

where $E_{d,fi}$ – design effect of actions for fire situation, N/mm^2,

$R_{d,fi}$ – design resistance in the fire situation, N/mm^2.

4.2 Charring depth

4.2.1 Notional charring depth and rate

The notional charring depth is a charring depth that includes the effect of corner roundings. It is calculated for all charring phases according to the formula (4.3) [6].

$$d_{char,n} = \beta_n t, \tag{4.3}$$

where $d_{char,n}$ – notional design charring depth, mm,

β_n – notional design charring rate, which includes the effect of corner roundings and fissures,

t – the time of fire exposure, min.

The notional charring rate varies and it is calculated for respective charring phase according to formula (4.4) [6].

$$\beta_n = \prod_{k_i} k_i \, \beta_0, \tag{4.4}$$

where $\prod_{k_i} k_i$ – product of applied modification factors,

β_0 – basic design charring rate, mm/min.

4.1.3 Modification factors

Modification factors are used in the calculation of the notional charring rate.

Modification factor k_{gd} takes into account the increased heat flux in the grain direction as equation (4.5) follows [6].

$$k_{gd} = \begin{cases} 1{,}0 & \text{for heat flux perpendicular to the grain direction} \\ 2{,}0 & \text{for heat flux in the grain direction} \end{cases} \tag{4.5}$$

In this thesis, heat flux is perpendicular to the grain direction; therefore $k_{gd} = 1{,}0$ [6].

Another modification factor is k_n. It is the conversion factor that considers the effect of corner roundings and the effect of cracks and fissures on the surface of the linear member. The value for k_n for other than circular members should be taken as in equation (4.6) [6].

$$k_n = \begin{cases} 1{,}23 & \text{for solid linear timber members made of softwood and beech} \\ 1{,}08 & \text{for all other linear timber members} \end{cases} \quad (4.6)$$

This research is about glulam linear members; therefore, $k_n = 1{,}08$ [6].

4.3 Initially unprotected sides of members

Initially unprotected sides of glued and solid members with maintained glue line integrity have one linear charring phase as shown in Figure 4.1 [6].

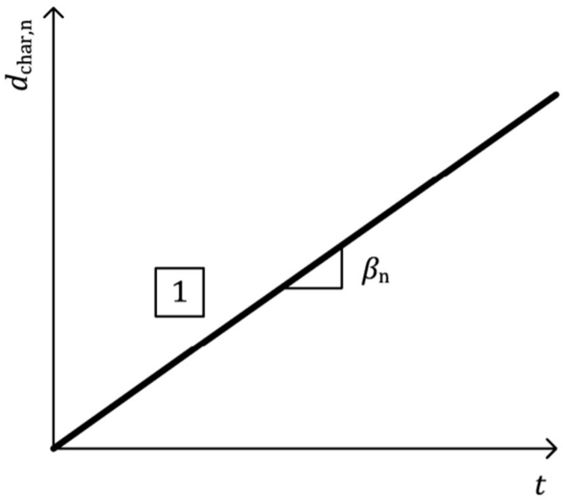


Figure 4.1 Charring depth of initially unprotected member:
1 – normal charring phase (phase 1), t – time, $d_{char,n}$ – notional charring depth, β_n – notional charring rate.

For initially unprotected members, the notional charring rate β_n should be calculated using formula (4.7) [6].

$$\beta_n = \prod_{k_i} k_i \, \beta_0 = k_{gd} k_n \beta_0, \quad (4.7)$$

4.4 Initially protected sides of members

Initially protected sides of members have up to 4 charring phases [6]. The phases and the calculation of the charring depth of initially protected members are elaborated on in the next sections.

4.4.1 Charring phases of initially protected members

As previously mentioned, initially protected members have more charring phases than initially unprotected members. Encapsulated, protected, post-protected and consolidated are the charring phases that occur in the charring of initially protected members. The encapsulated phase (Phase 0) is the phase when no charring occurs. The protected phase (Phase 2) is the phase when charring occurs behind the protection. The post-protected phase (Phase 3) is the phase after the failure of protection and before the char layer is fully developed. The consolidated phase (Phase 4) is the phase after the char layer is fully developed [6].

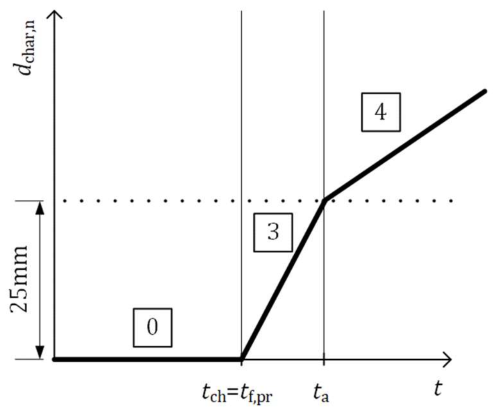


Figure 4.2 Charring of initially protected sides of timber members when $t_{f,pr}=t_{ch}$ and the charring depth at t_a is 25 mm [6]

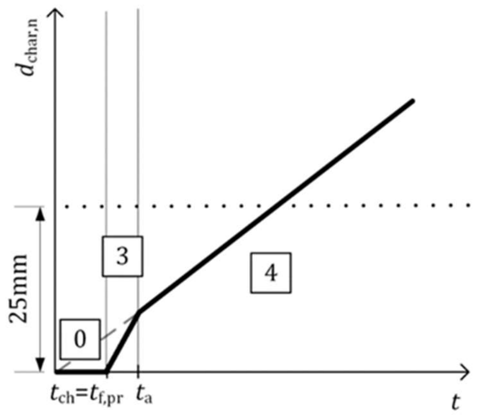


Figure 4.3 Charring of initially protected sides of timber members when $t_{f,pr}=t_{ch}$ and the charring depth at t_a is less than 25 mm [6]

As can be seen in Figure 4.2 and Figure 4.3, an initially protected member that has the start time of charring equal with the failure time of protection has 3 different charring phases. The encapsulated phase spans from the beginning of the fire until time t_{ch}. The charring begins after time t_f, when the failure of the protective layer occurs. This is followed by phase 3, where charring takes place at a higher rate than the charring in phase 1. The notional charring rate in phase 3 is calculated according to formula (4.8) [6].

$$\beta_{n,phase3} = \prod_{k_i} k_i \, \beta_0 = k_{gd} k_n k_3 \beta_0, \tag{4.8}$$

For members that are not in timber frame assemblies, the post-protection factor k_3 for the post-protective phase should be taken as equation (4.9) states [6].

$$k_3 = 2{,}0. \tag{4.9}$$

The phase 3 ends at t_a and then phase 4 begins. The notional charring rate in phase 4 is calculated according to the following formula (4.10) [6].

$$\beta_{n,phase4} = \prod_{k_i} k_i \, \beta_0 = k_{gd} k_4 \beta_0, \tag{4.10}$$

The consolidation factor k_4 should be taken as equation (4.11) follows [6].

$$k_4 = 1{,}0. \tag{4.11}$$

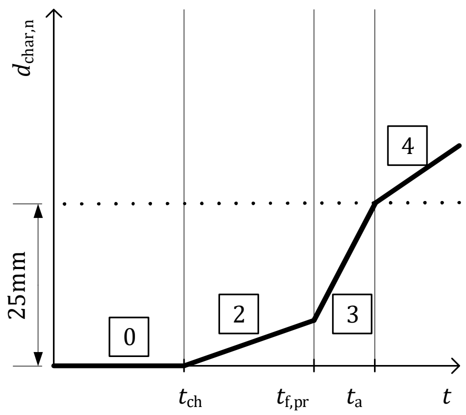


Figure 4.4 Charring of initially protected sides of timber members when $t_{f,pr} > t_{ch}$ [6]

If $t_{ch} < t_f$ as in Figure 4.4, then there is also phase 2 in addition to phases 0, 3 and 4. During the protected phase, the notional charring rate is lower than in phases 1, 3 and 4. The notional charring rate in phase 2 is calculated according to formula (4.12) [6].

$$\beta_{n,phase2} = \prod_{k_i} k_i \, \beta_0 = k_{gd} k_n k_2 \beta_0, \tag{4.12}$$

where k_2 – the modification factor.

If gypsum fibreboards or gypsum plasterboards are used, k_2 should be calculated using the formula (4.13) [6].

$$k_2 = 1 - \frac{h_p}{55}, \tag{4.13}$$

where h_p – the thickness of the gypsum plasterboards or gypsum fibreboards, mm.

4.4.2 The failure time of the fire protection system

The failure time $t_{f,pr}$ of the fire protection systems depends on the type of protection and the number of protective layers. If the protection time is applied to linear members, then the failure time is increased by 20% [6]. In this thesis, 20% increased formulas for walls are used for columns and 20% increased formulas for ceilings are used for ceilings as shown in Table 4.1 [6].

Table 4.1 Failure times of protection [6]

One layer of GtF for column	$t_{f,pr} = 1{,}2(3{,}9h_p - 16)$	(4.14)
One layer GtA for column	$t_{f,pr} = 1{,}2(1{,}8h_p - 5)$	(4.15)
One layer of GtF for beam	$t_{f,pr} = 1{,}2(1{,}6h_p + 3)$	(4.16)
One layer GtA for beam	no formula	

where h_p – thickness of layer, mm.

If there is no rule given for the failure time $t_{f,pr}$, the failure time is taken as the formula (4.17) follows [6]. In this research, this formula is used in the failure time calculations of one layer of GtA on a beam.

$$t_{f,pr} = t_{ch} = \sum t_{prot}, \tag{4.17}$$

where $\sum t_{prot}$ – the sum of protection times of the fire protection system for separating function, min,

t_{ch} – the start time of charring, min.

4.4.3 The start time of charring

The time of the beginning of charring behind the protection system should be calculated based on the following formula (4.18) [6].

$$t_{ch} = min\begin{cases} \sum t_{prot} \\ t_{f,pr} \end{cases}, \tag{4.18}$$

The protection time is calculated according to the following formula (4.19) [6].

$$t_{prot,i} = (t_{prot,0,i} \cdot k_{pos,exp,i} \cdot k_{pos,unexp,i} + \Delta t_i) \cdot k_{j,i}, \tag{4.19}$$

where $t_{prot,0,i}$ – the basic protection time of the considered layer I, min,

$k_{pos,exp,i}$ – position coefficient that takes into account the influence of layers preceding the layer considered,

$k_{pos,unexp,i}$ – position coefficient that takes into account the influence of layers backing the layer considered,

Δt_i – the correction time for layer i, min.

$k_{j,i}$ – the joint coefficient for the layer.

As in this thesis Δt_i=0 and all the other components of the formula other than $t_{prot,0,i}$ are equal to 1, the protection time can be taken equal with $t_{prot,0,i}$ [6]. In this research only one layer and one type of protective layer at time is used on the members. Consequently, the sum of protection times of the fire protection system can be calculated according to formula (4.20) [6].

$$\sum t_{prot} = t_{prot,0,i} = 30\left(\frac{h_p}{15}\right)^{1,2}, \tag{4.20}$$

where h_p – thickness of layer, mm.

4.4.4 Time of reaching the encapsulated phase

The time t_a, when the char layer is fully developed, should be calculated using the following formula (4.21) [6].

$$t_a = min\begin{cases} 2\,t_{f,pr} \\ t_{f,pr} + \dfrac{25 - (t_f - t_{ch})\beta_{n,phase2},}{\beta_{n,phase3}} \end{cases} \tag{4.21}$$

The char layer has fully developed if the depth of the char layer reaches 25mm or the depth of the char layer of the initially unprotected member [6].

4.5 Effective cross-section of linear members

The effective charring depth for each fire exposed side should be calculated according to formula (4.22) [6].

$$d_{ef} = d_{char,n} + d_0, \tag{4.22}$$

where d_{ef} – the effective charring depth, mm,

$d_{char,n}$– the notional charring depth, mm,

d_0 – depth of zero-strength layer, mm.

The depth of the notional char layer is calculated according to the previous sections. The zero-strength layer depth is taken in accordance with Table 4.2 and Figure 4.5.

Table 4.2 Values of zero-strength layer depth d_0 for linear members [6].

Stress	**R30 / mm**	**R60 and more / mm**
Bending	7	10
Compression	14	16

For fire resistance between 30 and 60 minutes, values of zero-strength layer depth may be interpolated linearly [6]. The permission is not applied in this thesis.

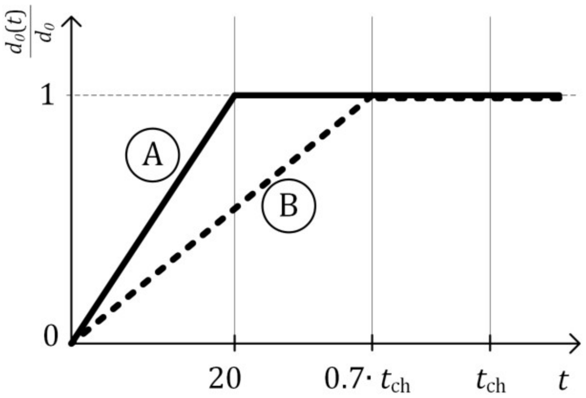


Figure 4.5 Determination of the value of zero-strength layer depth d_0 as a function of the time, A – increase of the zero-strength layer depth for initially unprotected members, B – increase of the zero-strength layer depth for initially protected members

The effective width of an effective cross-section shall be calculated as formula (4.23) follows [6].

$$b_{ef} = b - k_{sides} d_{ef}, \tag{4.23}$$

where b_{ef} – the effective width of effective cross-section, mm,

b – the initial width of cross-section, mm,

d_{ef} – effective depth of charring, mm.

The effective height of an effective cross-section should be calculated according to formula (4.24) [6].

$$h_{ef} = h - k_{sides} d_{ef}, \tag{4.24}$$

where h_{ef} – the effective height of effective cross-section, mm,

h – the initial height of cross-section, mm,

k_{sides} – number of respective opposite sides exposed to fire,

5. CALCULATIONS NOT BASED ON EN 1995-1-2

In this research, columns are subjected to compression.

Stability of members

The stability of members is not covered in EN 1995-1-2 but is in EN 1995-1-1. As there was no accessibility to the EN 1995-1-1:2020 draft, the stability calculations are based on EN 1995-1-1:2005. As the columns have equal height and width, it is necessary to evaluate the slenderness corresponding to bending only in one direction.

The moment of inertia for rectangular members is calculated according to formula (5.1) [13].

$$I_y = \frac{bh^3}{12}, \tag{5.1}$$

where b – the width of cross-section, mm,

h – the height of cross-section, mm.

As we are analysing the stability of a charred member, the formula (5.1) takes a formation of formula (5.2), where the dimensions of cross-section are replaced with the effective height and effective width of a charred member.

$$I_y = \frac{b_{ef} {h_{ef}}^3}{12}, \tag{5.2}$$

where I_y – the moment of inertia, mm^4,

b_{ef} – the effective width of effective cross-section, mm,

h_{ef} – the effective height of effective cross-section, mm.

As we know the effective cross-section and the moment of inertia, it is possible to calculate the radius of gyration, using the formula (5.3) [13].

$$i_y = \sqrt{\frac{I_y}{A}}, \tag{5.3}$$

where i_y – the radius of gyration, mm,

I_y – the moment of inertia, mm^4,

A – the area of effective cross-section, mm^2.

The relative slenderness ratio $\lambda_{rel,y}$ is calculated according to formula (5.4) [14].

$$\lambda_{rel,y} = \frac{\lambda_y}{\pi}\sqrt{\frac{f_{c,0,k}}{E_{0,05}}}, \tag{5.4}$$

where λ_y – slenderness ratio corresponding to bending about the y-axis,

$f_{c,0,k}$ – the compressive strength along the grain,

$E_{0,05}$ – the fifth percentile value of the modulus of elasticity parallel to the grain.

The slenderness ratio corresponding to bending about the y-axis is calculated as the formula (5.5) follows [13].

$$\lambda_y = \frac{l_{ef}}{i_y}, \tag{5.5}$$

where l_{ef} – the effective length of member, mm.

The effective length is calculated according to formula (5.6) [13].

$$l_{ef} = \mu l, \tag{5.6}$$

where μ – the support factor.

In this thesis, μ =0,7 [9].

If the relative slenderness ratio satisfies condition $\lambda_{rel,y} \leq 0{,}3$, then the stresses should satisfy the following condition (5.7) [9].

$$\sigma_{c,0,d} \leq f_{c,0,d}, \tag{5.7}$$

where $\sigma_{c,0,d}$ – the design compressive stress along the grain, N/mm^2,

$f_{c,0,d}$ – the design compressive strength along the grain, N/mm^2.

If the relative slenderness ratio does not satisfy the condition, then the stress should satisfy the following condition (5.8) [9].

$$\sigma_{c,0,d} \leq k_{c,y} f_{c,0,d}, \tag{5.8}$$

where $k_{c,y}$ – instability factor.

The instability factor $k_{c,y}$ is calculated according to formula (5.9) [14].

$$k_{c,y} = \frac{1}{k_y + \sqrt{k_y^2 - \lambda_{rel,y}^2}}, \tag{5.9}$$

To calculate the instability factor $k_{c,y}$, another instability factor k_y is needed. The instability factor k_y is calculated according to formula (5.10) [14].

$$k_y = 0{,}5(1 + \beta_c(\lambda_{rel,y} - 0{,}3) + \lambda_{rel,y}^2), \tag{5.10}$$

where $\lambda_{rel,y}$ – relative slenderness ratio,

β_c – straightness factor.

The straightness factor β_c for glulam timber is 0,1 [14].

Combined bending and axial compression

If the column is compressed eccentrically, then the column is both compressed and bended. The bending moment of an eccentrically compressed column is calculated according to formula (5.11) [13].

$$M = F \cdot e, \tag{5.11}$$

where F – applied force, kN,

e – eccentricity, m.

The compressive stress of an eccentrically compressed column is calculated using the equation (5.12) [13].

$$N = F, \tag{5.12}$$

A member subjected to both compression and bending shall satisfy the following expressions (5.13) and (5.14) [14]. The applied force F is found by the trial and error method, so that the expressions are satisfied.

$$\left(\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right)^2 + \frac{\sigma_{m,y,d}}{f_{m,y,d}} + k_m \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1, \tag{5.13}$$

$$\left(\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right)^2 + k_m \frac{\sigma_{m,y,d}}{f_{m,y,d}} + \frac{\sigma_{m,z,d}}{f_{m,z,d}} \leq 1, \tag{5.14}$$

where $\sigma_{c,0,d}$ – design compressive stress along the grain, N/mm^2,

$f_{c,0,d}$ – design compressive strength along the grain, N/mm^2,

$\sigma_{m,y,d}$ – design bending stress about the principal y-axis, N/mm^2,

$f_{m,y,d}$ – design bending strength about the principal y-axis, N/mm^2,

$\sigma_{m,z,d}$ – design bending stress about the principal z-axis, N/mm^2,

$f_{m,z,d}$ – design bending strength about the principal z-axis, N/mm^2,

k_m – factor considering re-distribution of bending of stresses in apex zone.

The factor k_m for rectangular sections is 0,7 [14].

As the location of eccentrically applied force is unknown, then in calculations, the force is chosen to be applied on the y-axis. As a result, the expressions (5.11) and (5.12) take the following formations in (5.15) and (5.16).

$$\left(\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right)^2 + \frac{\sigma_{m,y,d}}{f_{m,y,d}} \leq 1, \tag{5.15}$$

$$\left(\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right)^2 + 0{,}7 \frac{\sigma_{m,y,d}}{f_{m,y,d}} \leq 1, \tag{5.16}$$

As in this thesis, the lowest applied force causing the failure is examined; the formula (5.16) is then omitted.

The design strengths $f_{c,0,d}$ and $f_{m,y,d}$ are taken from European standard EN 14080:2013 [11].The design compressive stress along the grain $\sigma_{c,0,d}$ is calculated according to formula (5.17) [13].

$$\sigma_{c,0,d} = N \cdot A = N \cdot b_{ef} \cdot h_{ef}, \quad (5.17)$$

where b_{ef} – effective width, m,

h_{ef} – effective height, m.

The design bending stress about the principal y-axis $\sigma_{m,y,d}$ is calculated according to formula (5.18) [13].

$$\sigma_{m,y,d} = \frac{M}{W} = \frac{M,}{\frac{b_{ef} h_{ef}^2}{6}}, \quad (5.18)$$

6. COMPARISON OF EN 1995-1-2:2004 AND EN 1995-1-2:2020

6.1 Differences in calculations of glulam linear members

Strength parameters

As in fire design the strength parameters are not the same as in the normal temperature design, it is necessary to calculate the strength parameters. The calculations of strength parameters are presented in Appendix 1 in this thesis for the 2004 version of Eurocode 5 and in Appendix 8 for the 2020 version of Eurocode 5.

In this thesis, the values of the fire design strength parameters are the same in calculations according to the 2004 and 2020 versions of Eurocode 5. However, the formulas have changed in the 2020 version and therefore the calculations are different. In the 2004 version of Eurocode 5, formula (3.2) is used to calculate the 20% fractile of strength property and then the result is used in formula (3.1) to calculate the design strength in fire. In the 2020 version of Eurocode 5, the 20% fractile is not calculated separately, but the 2 formulas are combined in one formula (4.1). Furthermore, in the 2020 version, instead of modification factor $k_{mod,fi}$, the temperature-dependent reduction factor for a strength and stiffness k_Θ is used. However, both factors are taken as 1,0 for the Effective Cross-Section Method.

Charring of unprotected member

The principles of the charring process of unprotected linear members are the same in both versions of Eurocode 5. Nevertheless, the charring rate has slightly changed. While the notional charring rate for glulam in the 2004 version was given as 0.7 mm/min, in the 2020 version it is calculated according to the formula (4.7). As seen in Appendix 9, according to the 2020 version, the notional charring rate for glulam linear members is 0,702 mm/min, which is 0,002 mm/min higher than in the previous version. The change is still very small.

Start time of charring

If the timber member has a protective layer on it, then the start of charring is delayed until the time t_{ch}. In this research, 2 types of protection were used – 1 layer of GtA 12,5 and 1 layer of GtF 15. The 2004 version of Eurocode 5 uses formula (3.5) to calculate the start time of charring for claddings made of gypsum plasterboard type A and type F. In the 2020 version, the calculation of the start time of charring is performed by formulas (4.18)-(4.19) and is more complex. While one formula is suited for all GtA and GtF claddings in EN 1995-1-2:2004, GtA and GtF claddings have different formulas for the start time of charring in the new Eurocode 5. In this thesis, formula (4.20) is used in the case of 1 layer of GtA on the beam; in other cases, (4.18) and (4.14)-(4.16) are applied. In the 2020 version, there are also different rules for the failure time of the fire protection system of walls and ceilings. Those rules can be applied to linear members by increasing the results by 20% and the formulas are used to calculate the start time of charring. If the 20% increased start time of charring exceeds failure time of protection, the start time of charring is taken equal to the failure time of protection.

Failure time of protection

In the fire design models, an important point is the failure time of the protection system. In EN 1995-1-2:2004 the failure times of protection were not provided unless the failure time was taken equal to start time of charring. In the 2020 version, the failure time of protection is used in calculating the start time of charring. As analysed in the previous point, in the 2020 version, the failure time of the fire protection system of walls and ceilings have different rules for GtA and GtF protection systems and can be applied to linear members as presented in formulas (4.14)-(4.16). In case of 1 layer of GtA on beam, the failure time is equal to the start time of charring as formula (4.17) states.

In the 2004 version of Eurocode 5, the formula (3.6) states that the failure time of the protection system made of GtA is equal to the start time of charring. However, the 2004 version has no rule for the failure time of the protective cladding made of GtF. In this research, formula (3.7) was used to calculate the failure time of a fire protection system made of GtF cladding.

According to the 2020 version the failure time of the fire protection system applied to linear members may be increased by 20%.

Time of reaching the consolidated charring phase

After the failure time of protection, the next important point is the time of reaching the consolidated charring phase. The concept of phases is introduced in EN 1995-1-2:2020. In EN 1995-1-2:2004 phases were described by the start and end time of the phase and as a relationship between $d_{char,n}$ and time.

In the 2004 version of Eurocode 5, it is calculated according to formula (3.8) for members without protected charring phase and according to formula (3.9) for members with a protected charring phase. In the 2020 version, those 2 formulas are combined into one (4.21) and there is no longer a difference in the t_a calculation for members with or without a protected charring phase. Furthermore, a part of formula (3.8) is no longer used. The calculation process for the time of reaching the consolidated phase is easier for the user in the 2020 version, as there are fewer rules to be followed.

Protected charring phase

If the start time of charring and the failure time are not equal, then the charring occurs behind the protective cladding. In the protected charring phase, the charring rate is lower than in the unprotected charring. In the 2004 version of Eurocode 5, the given notional charring rate was multiplied by the factor k_2 calculated according to formula (3.4). In the 2020 version, the charring rate is calculated according to formula (4. 12) and (4.13). In addition to the changes that also occur in the calculation process of an unprotected member, there is a change in the k_2 formula. Nevertheless, the change does not affect the result. In the newer version of the Eurocode 5, the coefficient that is multiplied by the thickness of protective cladding is given as a fraction and not as a decimal, as was the case in the previous version.

Post-protected charring phase

After the failure of protection, the charring occurs in a higher rate than the charring of an unprotected member. In this charring phase, in the 2004 version the notional charring rate is multiplied by k_3 and in the 2020 version, the notional charring rate is calculated according to the formula (4.8). As the coefficient k_3 is the same in both versions of the Eurocode 5, the only differences that occur are the same that are also in the charring of unprotected member that is analysed afore.

Consolidated charring phase

The last charring phase of protected members is the consolidated charring phase. In the 2004 version, the charring rate in this phase equals the charring rate of the unprotected member. In 2020 version, in the consolidated phase the charring rate is multiplied by coefficient k_4, that equals 1. Again, the only differences that occur are the same that also occur in the charring of unprotected member.

Effective cross-section

In both versions, the effective cross-section is calculated by removing the effective charring depth from the initial cross-section. The calculation of the depth of the char layer is done according to the charring phases, charring rate and the duration of fire exposure. In the 2004 version of Eurocode 5, the effective charring depth is calculated using formula (3.10) and it consists of the sum of the notional charring depth and a multiplication of the depth of zero-strength layer d_0 and coefficient k_0. In that version, the depth of the zero-length layer is constant and coefficient k_0 is a variable from 0 to 1, which depends on the existence of the protection and the time of fire exposure. In the 2020 version, the effective depth of the char layer is calculated according to the formula (4.22). The depth of the zero-strength layer is no longer multiplied by a variable coefficient, but the zero-strength layer is a variable instead. The zero-strength layer varies according to the time of fire exposure and the type of stress. While the multiplication of d_0 and k_0 varied from 0 to 7 mm in the 2004 version, in the 2020 version d_0 varies from 7 to 16 mm. Consequently, the fire resistance of timber members according to the 2020 version of the Eurocode 5 is lower than it is according to the 2004 version.

6.2 Load-bearing capacity of beams

In this research, the beams are made of combined glulam from strength class GL24c. The applied force causes bending stress in the beams. The aim of the calculations is to find the highest applicable forces that do not cause a failure of the beams. The beams are exposed to fire from 3 sides. The time of standard fire in the calculations is 30, 60 and 90 minutes. The calculation examples are in appendices and the results are presented in Table 6.2. In the table and figures, EC5:2004 stands for EN 1995-1-2:2004 and EC5:2020 for EN 1995-1-2:2020. The references to Appendices consisting of calculation examples and results for beams are shown in Table 6.1.

Table 6.1 References to calcualtions about beams

Content	**EC5:2004**	**EC5:2020**
Calculations of the strength parameters	Appendix 1	Appendix 8
Calculations of initially unprotected glulam beam	Appendix 2	Appendix 9
Calculations of glulam beam with one layer of GtA 12,5	Appendix 3	Appendix 10
Calculations of glulam beam with one layer of GtF 15	Appendix 4	Appendix 11

6.2.1 The change of maximum bending moments

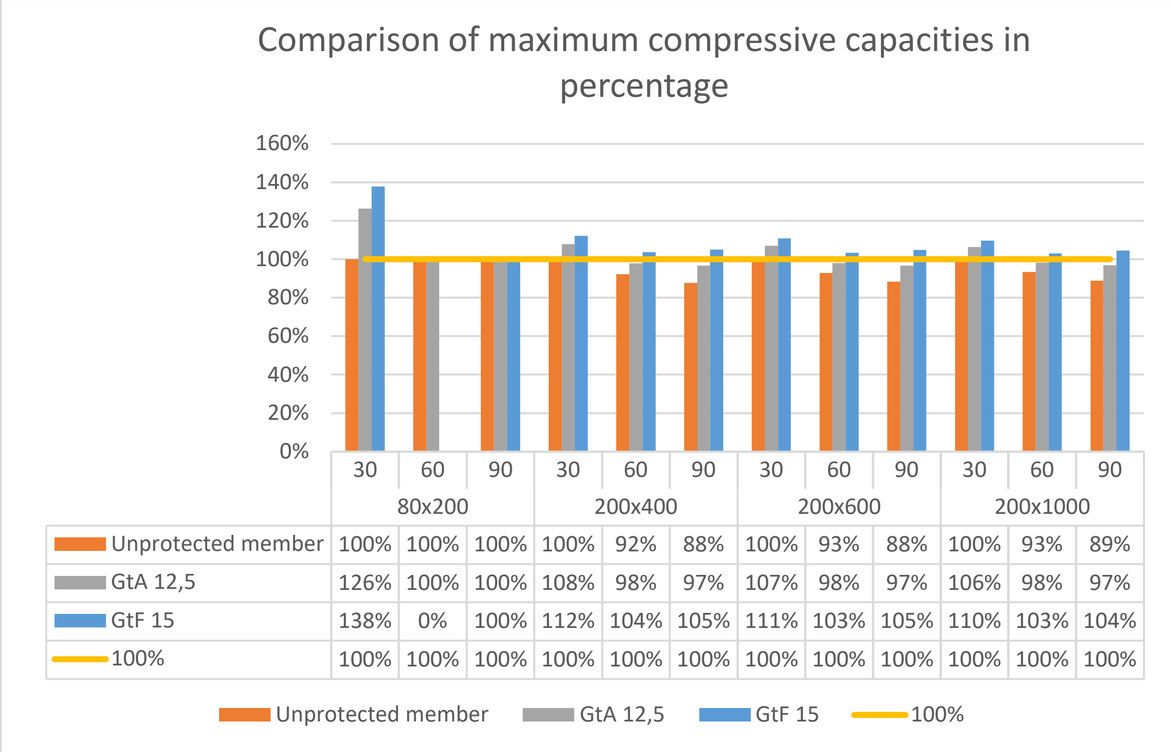
Table 6.2 Maximum bending moments on beams in kilonewtonmeters

Time		30 min		60 min		90 min	
Protective layer	Cross-section	EC5:2004	EC5:2020	EC5:2004	EC5:2020	EC5:2004	EC5:2020
None	80x200	3.2	3.2	0	0	0	0
	200x400	91.6	91.5	57.8	53.3	30	26.3
	200x600	216.7	216.5	142.4	132.2	77.5	68.4
	200x1000	625.8	625.2	424.3	395.7	238.7	211.9
GtA 12,5	80x200	6.1	7.7	0	0	0	0
	200x400	107	115.3	61	59.7	32.6	31.5
	200x600	249.1	266.4	149.7	146.7	83.9	81.1
	200x1000	710.9	755.8	444.7	436.3	257.4	249.2
GtF 15	80x200	8.2	11.3	0	0	0	0
	200x400	117.8	132.1	65.2	67.6	36.1	37.9
	200x600	271.6	300.8	159.2	164.4	92.1	96.5
	200x1000	769.2	843.6	470.8	485	281.5	294

As can be seen in Table 6.2, after 30 minutes of fire, the maximum bending forces on initially unprotected beams have stayed the same and on initially protected beams they have increased. However, after 60 and 90 minutes of fire, according to EN 1995-1-2:2020 beams protected with GtA 12,5 have smaller maximum bending forces than according to EN 1995-1-2:2004.

To have a better overview of the size of the change, the results of calculations according to 2020 version of Eurocode 5 were examined as a percentage of the results of calculations according to the 2004 version. The percentage was calculated according to formula (6.1) and the results are shown in Figure 6.1.

$$\frac{EC5:2020}{EC5:2004} \cdot 100\%, \tag{6.1}$$



	80x200			200x400			200x600			200x1000		
	30	60	90	30	60	90	30	60	90	30	60	90
Unprotected member	100%	100%	100%	100%	92%	88%	100%	93%	88%	100%	93%	89%
GtA 12,5	126%	100%	100%	108%	98%	97%	107%	98%	97%	106%	98%	97%
GtF 15	138%	0%	100%	112%	104%	105%	111%	103%	105%	110%	103%	104%
100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Figure 6.1 Comparison of maximum bending capacities on beams in percentage

As can be seen in Figure 6.1, after 30 minutes of fire the maximum bending capacities on initially unprotected beams have stayed the same. This is due to the same depth of the zero-strength layer and the same notional charring rate. After 60 minutes of fire, the maximum bending capacities have decreased on all other cross-sections but 80x200. The 80x200 cross-section has stayed the same, because the cross-section is fully charred by 60 minutes of fire and does not bear any loads. The maximum bending capacities on larger cross-sections have decreased because of the change in the depth of the zero-strength layer.

Figure 6.1 also shows, that the maximum bending capacities are the most significant among beams with one layer of GtF 15. After 30 minutes of fire, the maximum bending capacity according to EN 1995-1-2:2020 on the 80x200 cross-section is even 138% of the capacity according to EN 1995-1-2:2004. As the design strength of timber is the same according to both versions of Eurocode 5, the change is due to the effective depth of the cross-section and is the same in all cross-sections. The difference is smaller among larger cross-sections as the larger cross-sections can bear larger forces therefore, small changes affect the cross-section less. After 60 minutes of fire, the maximum bending capacity is still a little bit bigger on cross-sections that have not completely charred yet.

The increase of the maximum bending capacities can be noticed among beams with one layer of GtA after 30 minutes. Again, after 60 minutes of fire, the maximum bending capacity has decreased. The decrease is proportionally biggest on the 80x200 cross-section. The other cross-sections have a decrease in the maximum bending force due to the larger effective depth of the char layer than according to EN 1995-1-2:2004. The effective depth of the char layer is examined more thoroughly in the next section.

6.2.2 Effective depth of char layer on beams

The effective depth of the char layer consists of the depth of the notional char layer and the depth of the zero-strength layer. Figure 6.2 presents the change of notional charring depth on investigated types of beams in time according to both EN 1995-1-2:2004 and EN 1995-1-2:2020.

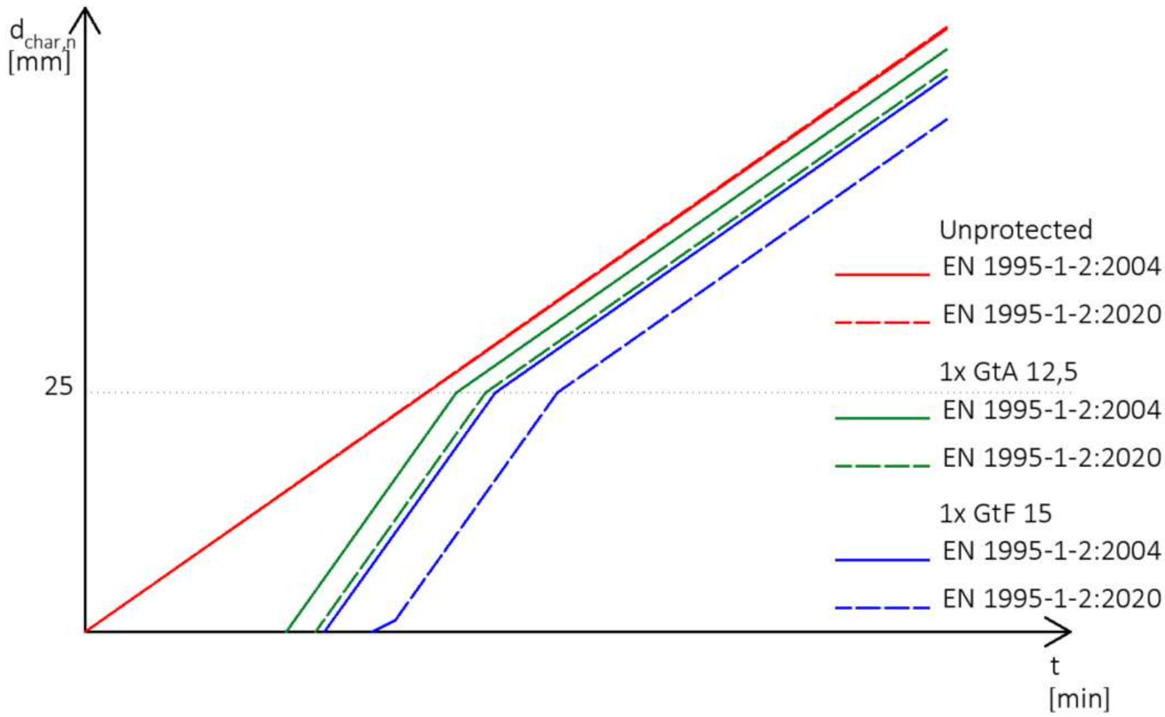


Figure 6.2 Charring depth of beams presented in this thesis:
$d_{char,n}$ – notional design charring depth.

As can be seen in Figure 6.2, the notional charring depth for initially unprotected beams has not significantly changed when comparing the 2004 and the 2020 versions of Eurocode 5. There is a small change due to the charring rate (see section 6.1.2). However, this change is very small.

On the other hand, the notional charring depth for initially protected beams has changed significantly. As shown in Figure 6.2, the notional charring depth for beams with one layer of gypsum plasterboard type A according to EN 1995-1-2:2020 is smaller than the notional charring depth according to EN 1995-1-2:2004. This is because, according to EN 1995-1-2:2020 t_{ch} and t_f have larger values than according to the 2004 version of Eurocode 5. The charring rate has changed marginally in all phases for beams with one layer of GtA 12,5.

Moreover, the notional charring rate for beams with protective system of one layer of GtF has changed. Similarly to beams with one layer of GtA it has decreased for all moments throughout charring. The failure time of protective cladding is much smaller in calculations according to EN 1995-1-2:2004. For both versions, the consolidated charring phase begins when the depth of the notional charring is 25 mm. However, as in phase 3, the notional charring depth is deeper in calculations according to EN 1995-1-2:2004; therefore, the beams calculated according to the 2020 version of Eurocode 5 reach the consolidated phase later than the beams calculated according to EN 1995-1-2:2004.

As mentioned above, the effective charring depth includes the depth of the zero-strength layer in addition to the notional charring depth. The depths of the zero-strength layer for members with bending stress are presented in Table 6.3.

Table 6.3 Depth of zero-strength layer for beams

time / min	**k_0d_0 (EC:2004) / mm**	**d_0 (EC:2020) / mm**
30	7	7
60	7	10
90	7	10

As can be seen in Table 6.3, the zero-strength layer in EN 1995-1-2004 is constant. However, this has changed in EN 1995-1-2:2020. Therefore, after 60 minutes of fire, the zero-strength layer increases by 3 mm from 7 mm to 10 mm.

The results of the effective depth of the char layer for beams are shown in

Table 6.4

Table 6.4 Effective depth of char layer for beams

Protective layer	**time / min**	**EC:2004 / mm**	**EC:2020 /mm**
None	30	28.00	28.06
	60	49.00	52.12
	90	70.00	73.18
GtA 12,5	30	19.60	15.28
	60	46.80	47.70
	90	67.80	68.76
GtF 15	30	8.02	7.00
	60	35.01	42.49
	90	56.01	63.55

As can be seen in

Table 6.4, the effective depth of the char layer has stayed almost the same for an initially unprotected beam after 30 minutes of fire. The 0,06 mm change comes from the difference in the charring rate. At 60 minutes, the depth of the zero strength layer increases by 3 mm, and that change can be seen in the effective depth of the char layer in initially unprotected members after 60 and 90 minutes of fire.

The effective depth of char layer of the beam with one layer of GtA 12,5 has decreased in calculations according to EN 1995-1-2:2020 after 30 minutes of fire. That is due the difference in the start time of charring. However, after 60 minutes, when the depth of the zero-strength layer increases, the effective depth of char layer of the beam with one layer of GtA 12,5 is bigger in calculations according to EN 1995-1-2:2020.

The effective depth of the char layer on beams with one layer of GtF 15 in calculations according to EN 1995-1-2:2020 after 30 minutes of fire consists only of the depth of the zero-strength layer. According to EN 1995-1-2:2004, however, the charring has already started and the effective depth of the char layer is larger and consists of both the zero-strength layer and the notional char layer; therefore, it is deeper. After 60 minutes of fire, the effective depth of the charring is deeper in calculations according to EN 1995-1-2:2004.

The graphs of the effective depths of charring in all the beams examined in this research are shown in Figure 6.3.

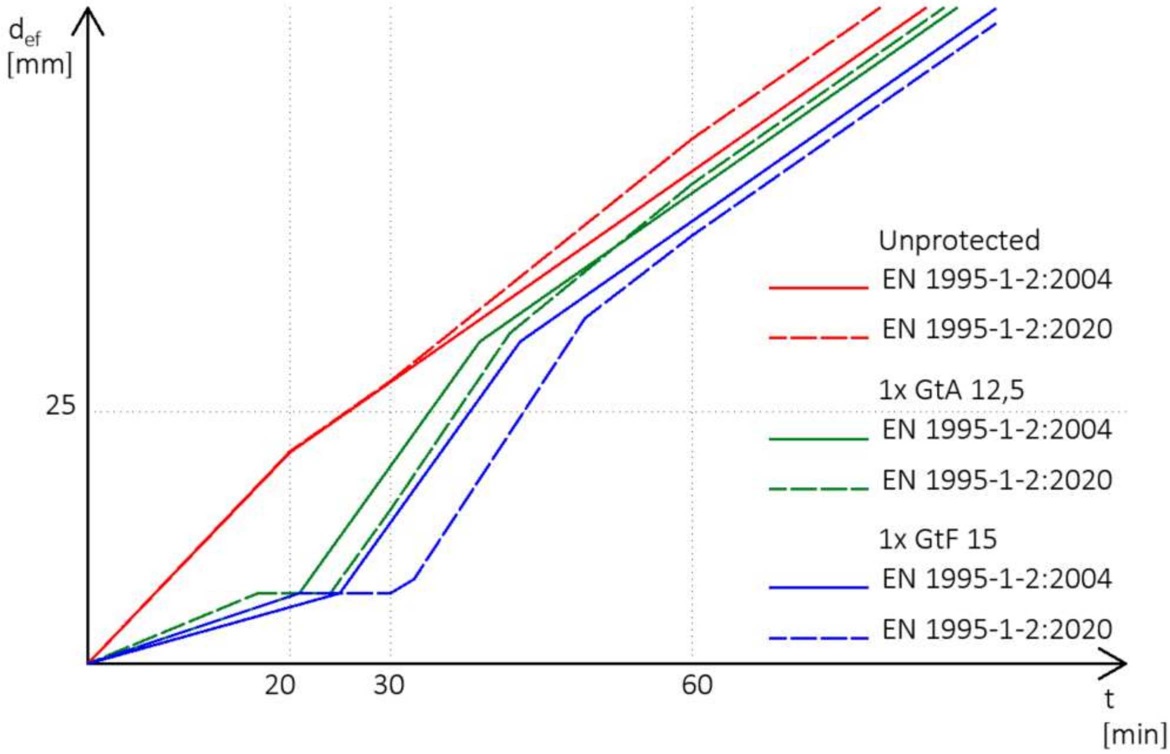


Figure 6.3 The change of the effective depth of the char layer on beams over time, d_{ef} – effective charring depth.

As can be seen in Figure 6.3 and as mentioned above, the effective depth of the char layer is almost the same for initially unprotected beams until 30 minutes of fire. Subsequently, according to EN 1995-1-2:2020, the depth of the zero-strength layer increases. Therefore, the effective depth of the char layer is deeper in calculations based on EN 1995-1-2:2020 after 30 minutes of fire.

The effective depth of the char layer on beams initially protected with one layer of gypsum plasterboard type A is deeper in calculations based on EN 1995-1-2:2020 at the beginning of charring. This is because, according to EN 1995-1-2:2020 the zero-strength layer develops faster than according to EN 1995-1-2:2004. The start of charring for beams with one layer of GtA occurs earlier according to EN 1995-1-2:2004, the depth of the zero-strength layer is equal. Because of that, the depth of the effective char layer is deeper in the phase 3 according to EN 1995-1-2:2004. The effective depth of the char layer is deeper again according to EN 1995-1-2:2020 from 53 minutes of fire, as then the depth of the zero-strength layer increases linearly by 3 mm and the difference in the notional charring depth is less than 3 mm.

Similarly, the effective char layer in phase 0 on beams with one layer of GtF is also larger in calculations according to EN 1995-1-2:2020. However, as in calculations according to EN 1995-1-2:2004, the start time of charring and the failure time are earlier than in calculations according to EN 1995-1-2:2020. In calculations according to EN 1995-1-2:2004, the effective depth of the char layer is deeper for all moments throughout charring.

6.3 Load-bearing capacity of columns

In this research, the columns are made of homogenous glulam from strength class GL24h. The length of the columns is 3 m. Buckling length is considered 2,1 m. The applied force causes compressive stress in the member. The aim of the calculations is to find the highest applicable load that does not result in failure of the member. The columns are exposed to fire from all 4 sides. The time of standard fire in the calculations is 30, 60 and 90 minutes. The calculation examples are in appendices and the results are presented in Table 6.6. In the table and in the figures, EC5:2004 stands for the 2004 version of Eurocode 5 and EC5:2020 for the 2020 version of Eurocode 5. The references to Appendices consisting calculation examples and results for columns are shown in Table 6.5.

Table 6.5 References to calcualtions about columns

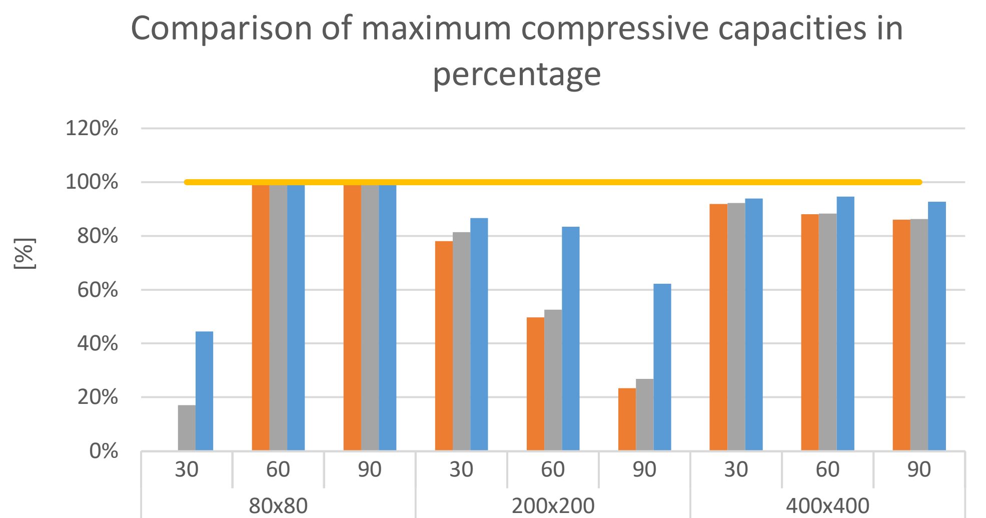
Content	**EC5:2004**	**EC5:2020**
Calculations of the strength parameters	Appendix 1	Appendix 8
Calculations of initially unprotected glulam column	Appendix 5	Appendix 12
Calculations of glulam column with one layer of GtA 12,5	Appendix 6	Appendix 13
Calculations of glulam column with one layer of GtF 15	Appendix 7	Appendix 14

6.3.1 The change of maximum compressive forces

Table 6.6 Maximum compressive forces on columns in kilonewtons

Time		30 min		60 min		90 min	
Protective layer	Cross-section	EC5:2004	EC5:2020	EC5:2004	EC5:2020	EC5:2004	EC5:2020
None	80x80	0.5	0	0	0	0	0
	200x200	406.1	317	157.8	78.4	21.8	5.1
	400x400	2538.9	2331.2	1946.8	1713.8	1432.3	1231.7
GtA 12,5	80x80	4.7	0.8	0	0	0	0
	200x200	520.7	424.1	180.9	95.1	28.7	7.7
	400x400	2797.6	2580.1	2005.1	1769.7	1482.5	1279.3
GtF 15	80x80	27.9	12.4	0	0	0	0
	200x200	696.3	603	317.6	264.9	94	58.5
	400x400	3169.5	2975.2	2332.6	2207.9	1766.4	1637

As can be seen in Table 6.6, maximum compressive forces are lower in calculations according to the 2020 version of Eurocode 5 than they are in calculations according to the 2004 version of Eurocode 5. To have a better overview of the size of the change the results of calculations according to the 2020 version of Eurocode 5 were examined as a percentage of the results of calculations according to the 2004 version. The percentage was calculated according to the formula (6.1) and the results are shown in Figure 6.4.



	80x80 30	80x80 60	80x80 90	200x200 30	200x200 60	200x200 90	400x400 30	400x400 60	400x400 90
Unprotected member	0%	100%	100%	78%	50%	23%	92%	88%	86%
GtA 12,5	17%	100%	100%	81%	53%	27%	92%	88%	86%
GtF 15	44%	100%	100%	87%	83%	62%	94%	95%	93%
100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Figure 6.4 Comparison of maximum compressive capacities on columns in percentage

As seen in Figure 6.4 and in Table 6.6, all the results have decreased in calculations according to EN 1995-1-2:2020. The results that have stayed the same (the percentage is 100%) have the value of 0 kN.

According to Figure 6.4, the smaller the cross-section, the bigger the difference in maximum compressive capacities. For example, the result of calculations according to EN 1995-1-2:2020 for a column with a protective layer of GtA and the initial cross-section of 400x400 after 30 minutes of standard fire is 92% of the result of calculations according to EN 1995-1-2:2004. Members exposed to the same duration of fire and with the same protective system but with initial cross-sections of 200x200 and 80x80 have the percentages of 81% and 17%, respectively. That correlation applies to all the protective systems. Although the difference in maximum compressive capacities in the larger cross-sections is proportionally small, the difference is still significant as larger cross-sections can take larger loads.

Figure 6.4 also shows that out of all the protection systems examined in this research the difference in results is smallest among members with a protective system made of one layer of GtF 15, and the change is largest among initially unprotected members. The results for columns with different protective layers are examined more thoroughly in the following sections.

Table 6.7 Change of maximum compressive capacities in percentage

Protective layer	**initial cross-section**	**time / min**	**EC:2004 / kN**	**EC:2020 / kN**	**Change** $\left(\frac{EC:2020-EC:2004}{EC:2004}\right)$ **/ %**
none	80x80	30	0.5	0	100%
		60	0	0	0%
		90	0	0	0%
	200x200	30	406.1	317	22%
		60	157.8	78.4	50%
		90	21.8	5.1	77%
	400x400	30	2538.9	2331.2	8%
		60	1946.8	1713.8	12%
		90	1432.3	1231.7	14%
GtA 12,5	80x80	30	4.7	0	100%
		60	0	0	0%
		90	0	0	0%
	200x200	30	520.7	424.1	19%
		60	180.9	95.1	47%
		90	28.7	7.7	73%
	400x400	30	2797.6	2580.1	8%
		60	2005.1	1769.7	12%
		90	1482.5	1279.3	14%
GtF 15	80x80	30	27.9	12.4	56%
		60	0	0	0%
		90	0	0	0%
	200x200	30	696.3	603	13%
		60	317.6	264.9	17%
		90	94	58.5	38%
	400x400	30	3169.5	2975.2	6%
		60	2332.6	2207.9	5%
		90	1766.4	1637	7%

As can be seen in Table 6.7, unless the cross-section has fully charred, maximum compressive capacity has changed the most among smaller cross-sections. This is due the depth of the effective char layer. Timber does not char in accordance with the dimensions of the column, but the effective char layer has an equal depth for all the cross-sections as can be seen in Appendices. Therefore, the char layer of larger cross-sections is proportionally smaller than the char layer of smaller cross-sections. This means that the larger the cross-section, the smaller is the change. That correlation applies to all the protective systems. If 80x80 cross-sections are completely charred between 30 and 60 minutes, larger cross-sections still have the load bearing cross-section after 90 minutes of fire. Nevertheless, it can be seen, that after 30 minutes of fire, the change is biggest among 80x80 cross-section and smallest among 400x400 cross-section.

6.3.2 Effective depth of char layer on columns

According to formulas (3.10) and (4.21), the effective charring depth is a sum of notional charring depth and a layer that is under the char layer and has zero strength. Figure 6.5 presents the change of notional charring depth in time according to both EN 1995-1-2:2004 and EN 1995-1-2:2020.

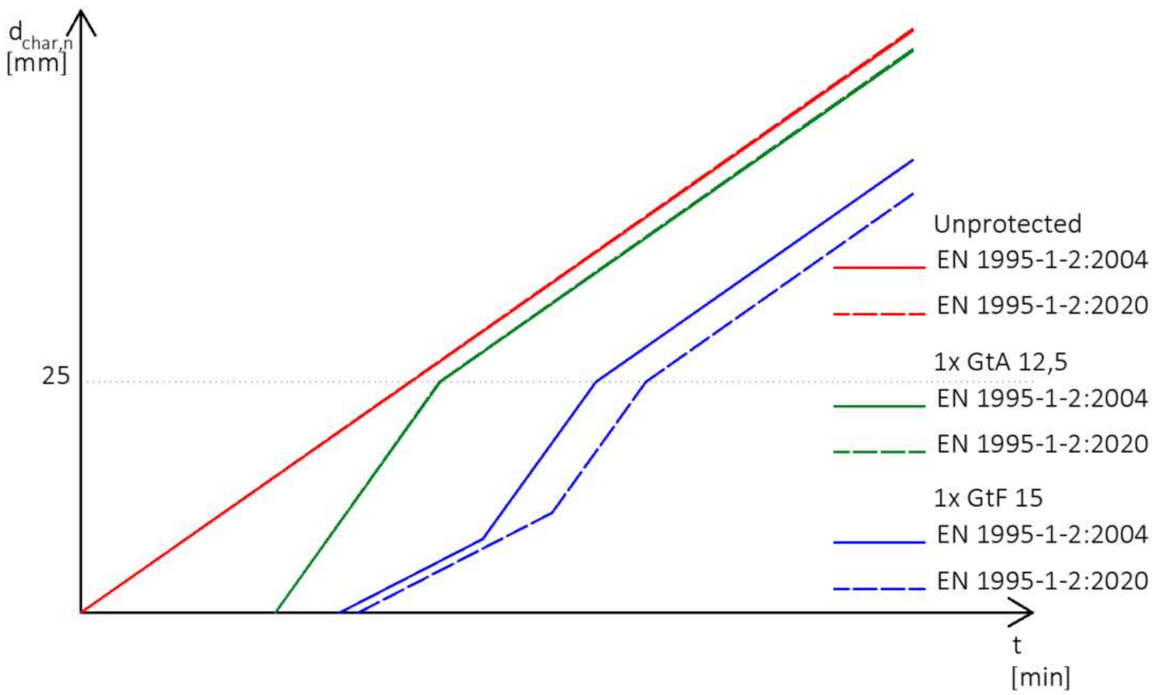


Figure 6.5 Charring depth of columns presented in this thesis,
$d_{char,n}$ – notional design charring depth.

As can be seen in Figure 6.5, the notional charring rate for initially unprotected columns has changed marginally. The notional charring rate for initially unprotected columns according to the 2020 version of Eurocode 5 is slightly larger than according to the 2004 version. That change is examined more thoroughly in section 6.1.2. However, this change is very small and does not significantly affect the results.

Similarly, the charring of columns with protective system of one layer of GtA 12,5 has changed insignificantly. The start of charring and the time of reaching the consolidated phase are the same according to both versions of Eurocode 5, at 21 minutes and 38,8 minutes, respectively. There is a slight change in the notional charring rate that is similar to the notional charring rate for an unprotected column.

On the other hand, the charring of initially protected columns with protective layer made of one layer of GtF 15 has changed. As seen in Appendix 7, the start time of the charring of columns with one layer of GtF 15 according to the 2004 version of Eurocode 5 is after 28 minutes of fire, and is after 30 minutes of fire according to the information presented in Appendix 14. As examined in section 6.1.3, in EN 1995-1-2:2004 one formula was used to calculate the start of charring for both GtA and GtF protective layers. In EN 1995-1-2:2020, this is based on the failure time of protection and the sum of protection times of the fire protection system. As can be seen in Figure 6.5, this change affects the depth of the notional char layer. According to EN 1995-1-2:2004, the char layer is thicker than calculations according to EN 1995-1-2:2020, as the charring starts earlier in the 2004 version.

What is more, the failure time of the GtF layer has changed from 43,5 minutes according to EN 1995-1-2:2004 to 51 minutes according to the 2020 version. As examined in section 6.1.4, the 2004 version of Eurocode 5 does not have a formula for the failure time of GtF layer. This has changed in the EN 1995-1-2:2020 version. The newer version of Eurocode 5 has formulas for t_f for different situations (depending on whether GtF is on the wall, ceiling, linear member, how many layers of GtF is used, etc.). As can be seen in Figure 6.5, these changes affect the depth of the notional char layer of columns. The depth of the notional char layer is smaller according to EN 1995-1-2:2020 than the depth of the notional char layer according to EN 1995-1-2:2004.

As mentioned before, the depth of the effective char layer is a sum of $d_{char,n}$ and the zero-strength layer. The values for the zero strength-layer are presented in Table 6.8.

Table 6.8 Depth of zero-strength layer for columns

time / min	**k_0d_0 (EC:2004) / mm**	**d_0 (EC:2020) / mm**
30	7	14
60	7	16
90	7	16

As can be seen in Table 6.8, the depth of the zero-strength layer has changed significantly. After 30 minutes of fire, the depth of the zero-strength layer according to EN 1995-1-2:2020 is twice as deep as it is according to EN 1995-1-2:2004. When the fire lasts longer at least 60 minutes, the difference is even larger. These changes affect the maximum compressive load that the columns can bear.

The effective depth of the char layer is presented in Table 6.9.

Table 6.9 Effective depth of char layer for columns

Protective layer	**time / min**	**EC:2004 / mm**	**EC:2020 /mm**
None	30	28	35.06
	60	49	58.14
	90	70	79.18
GtA 12,5	30	19.6	26.64
	60	46.8	55.88
	90	67.8	76.94
GtF 15	30	8.02	14
	60	35.01	39.4
	90	56.01	61.26

As can be seen in Table 6.9, in all situations in this thesis, the effective depth of char layer for columns has increased in the calculations based on EN 1995-1-2:2020.

While the notional depth of the char layer for initially unprotected columns and for columns with one layer of GtA did not differ among EN 1995-1-2 versions, the effective depth for these columns is significantly different. This change is due to the difference in the depth of the zero-strength layer.

The effective depth of the char layer has also increased for columns with a GtF 15 layer. Although the notional depth of the char layer for columns with GtF layer was deeper according to the EN 1995-1-2:2004 version, the effective depth of the char layer is deeper in calculations according to EN 1995-1-2:2020.

As has been noted, the effective depth of the char layer has increased for all examined columns. As an initial cross-section is reduced by the depth of the effective char layer, the deeper the effective char layer, the smaller the effective cross-section. As the strength of timber in fire has not changed in the EN 1995-1-2 version, the change of the effective char layer directly affects the final results of calculations – the maximum compressive loads for columns.

The change of effective depth of the char layer over time is shown in Figure 6.6.

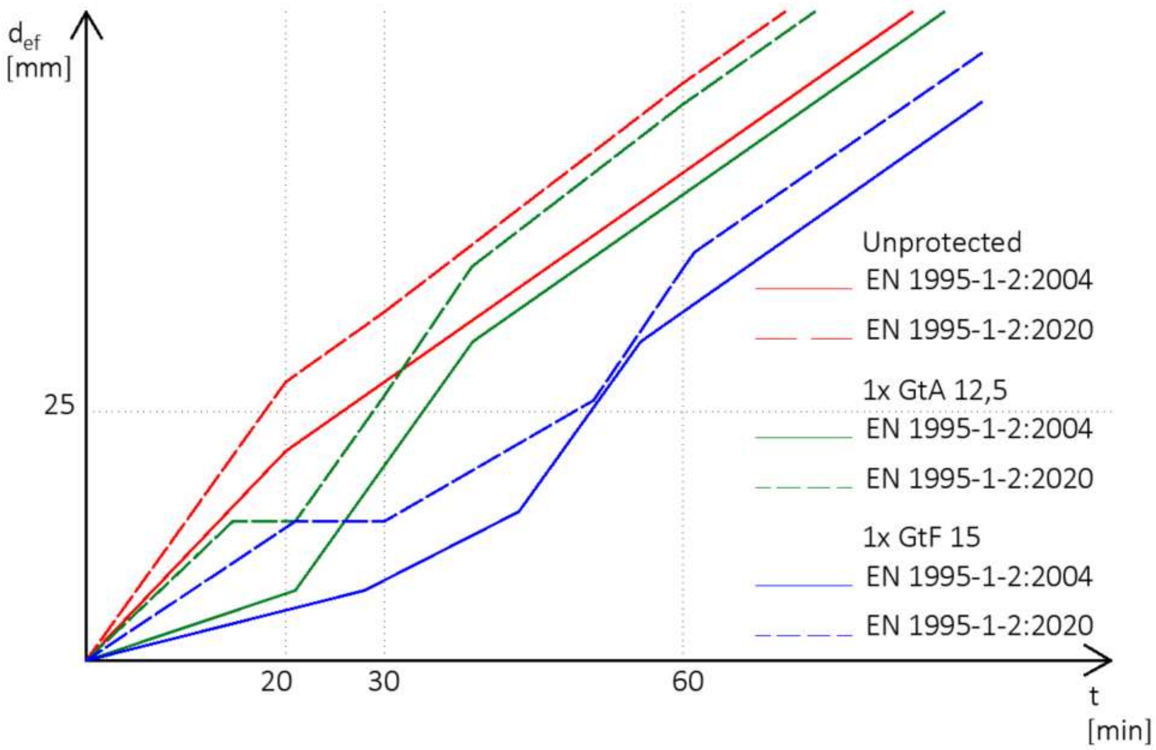


Figure 6.6 The change of the effective depth of the char layer over time,
d_{ef} – effective charring depth.

As can be seen in Figure 6.6, the effective depth of the char layer has increased for columns with one layer of GtA and for initially unprotected columns.

However, columns that are initially protected with one layer of GtF, for some time in the 3rd phase have an opposite outcome. The effective depth of the char layer according to EN 1995-1-2:2020 is lower than the effective depth of the char layer according to EN 1995-1-2:2004. This is due to differences in the $d_{char,n}$ as mentioned above.

It can also be noted, that according to EN 1995-1-2:2020 on initially protected columns, the zero-strength layer reaches the full depth before columns calculated according to EN 1995-1-2:2004. Furthermore, according to the 2020 version of Eurocode 5, after reaching the full depth, the zero-strength layer is no longer constant. It increases between 30 and 60 minutes linearly by 2 mm.

In conclusion, the maximum compressive load for glulam columns has decreased for all the examined columns. This is mainly due to change in the depth of the zero-strength layer.

7. COMPARISON OF FIRE RESISTANCE IN TESTS AND CALCULATION MODELS

In this thesis, 10 beams, previously tested in standard fire, have been compared to the results of calculations. Data and test results are taken from sources [15] and [16]. In Table 7.1, the initial cross-sections of tested beams, the type of protection used on beams and the strength class of beams are shown, in addition to the failure time of beams and the bending moment causing the failure. Beams 1-6 performed the 4-point t-bending tests before the fire tests and the mean bending strengths were determined. For beams from strength class GL24h, the mean strength was f_m = 31,2 N/mm^2 and for beams from strength class GL36h, the mean strength was f_m = 39,8 N/mm^2 [15].

Table 7.1 Parameters and results of beams tested in standard fire

NR	1 [15]	2 [15]	3 [15]	4 [15]	5 [15]	6 [15]	7 [16]	8 [16]	9 [16]	10 [16]
height / mm	254	256	256	253	253	217	362	600	599	600
width / mm	157	158	158	158	157	157	120	140	140	140
Protective layer	none	none	none	none	none	none	none	none	none	none
Strength class	GL24h	GL36h	GL36h	GL24h	GL36h	GL36h	GL24h	GL24h	GL32h	GL32h
time / min	52	49.25	68.88	48.1	58.28	44.4	48.2	32	24.5	13.5
bending moment / kNm	16.4	20.7	13.9	16	21	14.5	23	97	124.5	124.5

Calculations were made according to the cross-sections and failure times Table 7.1. The aim of the calculations was to find the maximum bending moment at the time when the tested beams failed. The calculations are shown in Appendix 15. The results are presented in Table 7.2. Figure 7.1 shows the results of calculations compared to the test results in percentage form. The percent in the figure is calculated in accordance with formula (7.1).

Table 7.2 Destructive bending moment and maximum bending moments

NR	1	2	3	4	5	6	7	8	9	10
Test / kNm	16.4	20.7	13.9	16	21	14.5	23	97	124.5	124.5
EC5:2004 / kNm	14.3	23.8	13.2	15.8	17.8	17.8	18.2	121.6	185.8	223.6
EC5:2020 / kNm	14.2	23.7	11.1	15.8	17.7	17.7	18.1	121.3	185.6	223.5

$$\frac{result\ of\ calculations}{result\ of\ tests} \cdot 100\%, \tag{7.1}$$

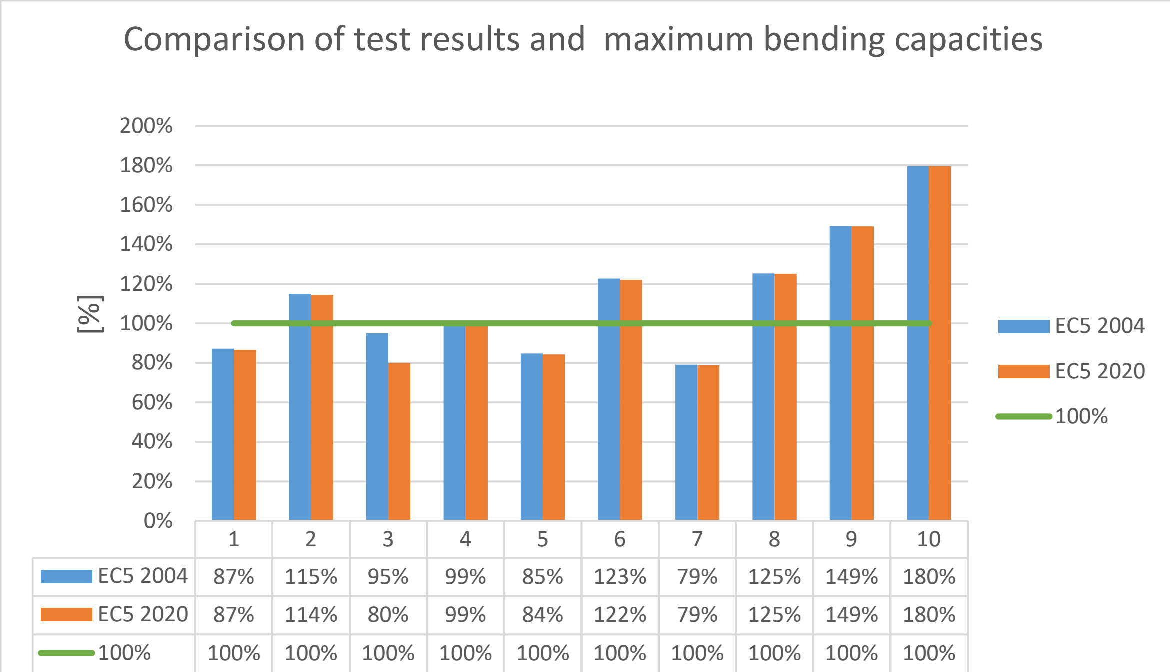
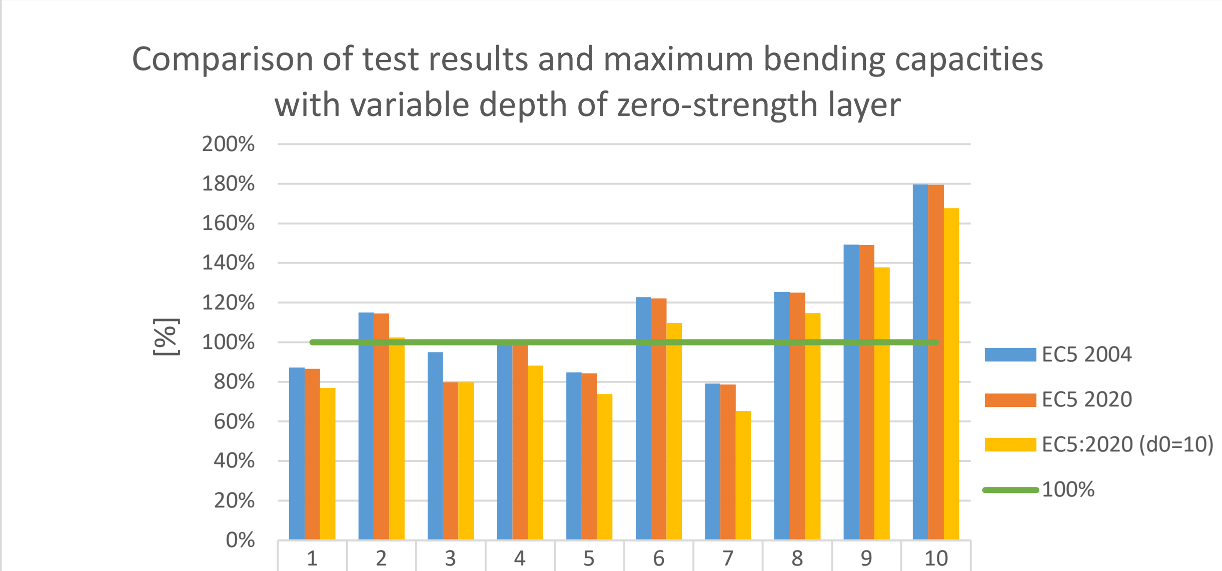


Figure 7.1 Comparison of maximum bending capacities to test results in percentage

As can be seen in Figure 7.1, calculations based on EN 1995-1-2:2020 estimate the maximum bending moment more conservatively than calculations based on EN 1995-1-2:2004. As the beams are initially unprotected, and most of the beams failed in tests before 60 minutes, the calculation results are rather similar to each other. However, calculations based on both versions of EN 1995-1-2 give too high maximum bending moments to beam numbers 2, 6 and 8-10. The reason for this could be that the depth of the zero-strength layer is not deep enough. The beams were recalculated according to EN 1995-1-2:2020, but the depth of the zero-strength layer before 60 minutes was taken at 10 mm instead of 7 mm. The results are shown in Table 7.3 and the results are compared to the previously calculated results in Figure 7.2.

Table 7.3 Maximum bending moment according to EN 1995-1-2:2020 when d_o=10 mm

NR	1	2	3	4	5	6	7	8	9	10
EC5:2020 / kNm	12.6	21.2	11.1	14.1	15.5	15.9	15	111.2	171.6	208.8



	1	2	3	4	5	6	7	8	9	10
EC5 2004	87%	115%	95%	99%	85%	123%	79%	125%	149%	180%
EC5 2020	87%	114%	80%	99%	84%	122%	79%	125%	149%	180%
EC5:2020 (d0=10)	77%	102%	80%	88%	74%	110%	65%	115%	138%	168%
100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

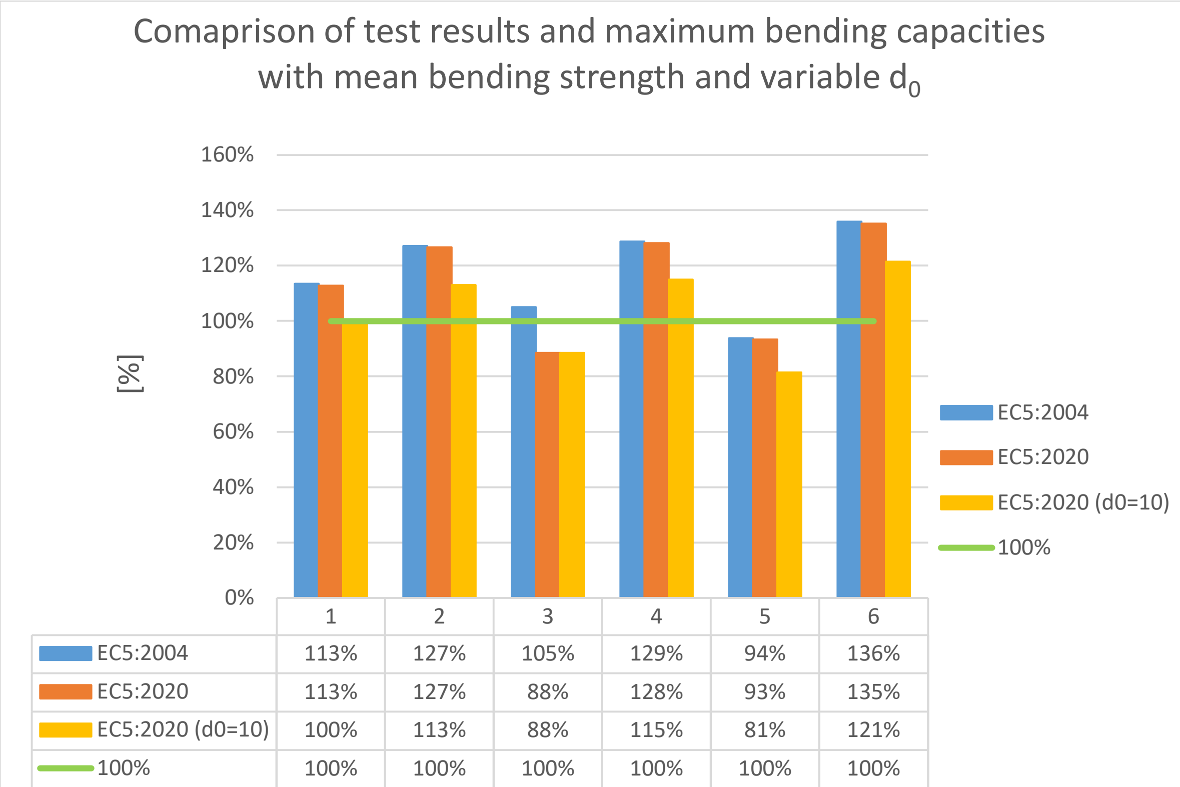
Figure 7.2 Comparison of test results and maximum bending capacities with variable d_0

Figure 7.2 shows that, as expected, the beams that failed before 60 minutes of fire have a lower result according to EN 1995-1-2:2020, with a 10 mm depth of zero-strength layer before 60 minutes of fire than the results of calculations with a 7 mm depth of zero-strength layer before 60 minutes. However, the results that exceeded 100% are still over 100%. Beams 2 and 6 are within a 10% error, but the calculation results for beams 8-10 are up to 168%. The reason could be that those beams did not fail in tests due to bending but instead due to losing their stability. The stability of beams is not considered in the calculations because there is no information of the length of beams 7-10.

During the tests on beams 1-6, the mean value of strength was measured. As the measured mean value of strength is closer to the real strength value of the beam, beams 1-6 were calculated with the mean bending strength value. The results are shown in Table 7.4 and they are compared to the test results according to formula (7.1) in Figure 7.3.

Table 7.4 Maximum bending moment with the mean strength value

NR	1	2	3	4	5	6
EC5:2004 / kNm	18.6	26.3	14.6	20.6	19.7	19.7
EC5:2020 / kNm	18.5	26.2	12.3	20.5	19.6	19.6
EC5:2020 / kNm (d_0=10 mm)	16.4	23.4	12.3	18.4	17.1	17.6



	1	2	3	4	5	6
EC5:2004	113%	127%	105%	129%	94%	136%
EC5:2020	113%	127%	88%	128%	93%	135%
EC5:2020 (d0=10)	100%	113%	88%	115%	81%	121%
100%	100%	100%	100%	100%	100%	100%

Figure 7.3 Comparison of test results and maximum bending capacities with mean bending strength and variable d_0

As can be seen in Figure 7.3, calculations with mean bending strength according to EN 1995-1-2:2004 and EN 1995-1-2:2020 are mostly above the test results. With the bending strength according to the strength class, only the calculation results of beams 2 and 6 were above the test results. As seen in Figure 7.3, in calculations with mean bending strength, 10 mm depth of the zero-strength layer gives more realistic results than calculations, where the depth of the zero-strength layer before 60 minutes is 7 mm.

In conclusion, the calculations estimate quite well the maximum bending moment of the beams. However, the calculation results are not very conservative, and, in some cases, calculations can overestimate the maximum bending capacity. This could be improved by increasing the depth of the zero-strength layer not only after 60 minutes of fire, but during the entire fire exposure time.

8. USER EXPERIENCE EVALUATION

8.1 Improvements in EN 1995-1-2:2020

EN 1995-1-2:2020 has more content than EN 1995-1-2:2004 and many aspects have been improved.

One of the improvements in EN 1995-1-2:2020 is the reference to coefficients. For example, in the calculation of the strength property, previously there was no reference where to find the value or formula for $k_{mod,fi}$. The user had to search through the standard to find the value for it. However, in EN 1995-1-2:2020, formulas have clear references to the sections where the modification factors for the strength of material can be found.

In addition, table 5.1 in EN 1995-1-2:2020 includes modification factors for charring and gives both a short designation for them and a reference to where each modification factor can be found. Consequently, the 2020 version of Eurocode 5 has a better structure and is more convenient for users.

Moreover, formula (3.3) in EN 1995-1-2:2004 that allows for applying the one-dimensional charring rate to non-planar surfaces has been removed from EN 1995-1-2:2020. To apply that formula, the rounding of corners had to be taken into account, but it was unclear as to what was the radius for corner roundings. Furthermore, rounded corners make it harder to find the characteristics for the effective cross-section. Therefore, the removal of this formula makes EN 1995-1-2:2020 more understandable and easier to use.

Another improvement in EN 1995-1-2:2020 is the charring phases. While the charring process was previously described by t_{ch}, t_f, t_a and charring between those times was described by the multiplication of modification factors and β_n, in the 2020 version of Eurocode 5, in addition to these, charring is also described by charring phases. The concept of charring phases makes the charring process easier to understand and describe.

One of the biggest obstacles in calculations according to EN 1995-1-2:2004 was the absence of the formula for the failure time of protective cladding made of GtF. However, this problem is solved in EN 1995-1-2:2020. To calculate the fire resistance for timber members with GtF, the user previously had to search the value of tf for GtF by themselves, but there are formulas to calculate it in EN 1995-1-2:2020. This is an important improvement for user experience.

Besides the formulas for the failure time of GtF, another improvement in the user experience in the calculation of the failure time is to eliminate the failure time of anchors. According to EN 1995-1-2:2004, the failure time of protection was the minimum of the failure time of anchors and the failure time of the protective cladding. In EN 1995-1-2:2020, the failure time is the time when the protective cladding fails and the anchors have to be long enough so that they do not become decisive for the failure of protection.

Furthermore, there have been some smaller improvements. One of them is the formula of modification factor k_2. In the newer version of Eurocode 5, the coefficient in the formula of k_2 that is multiplied by the thickness of protective cladding is given as a fraction not as a decimal, as it was given in the previous version. This change does not affect the value of the formula but makes the formula simpler and more user-friendly.

8.2 Deficiencies in EN 1995-1-2:2020

Although there are many improvements in EN 1995-1-2:2020, there are also some deficiencies in user experience.

First, under table 6.4 in EN 1995-1-2:2020, there is a condition, that to apply the failure time $t_{f,pr}$ to linear or plane members, the failure time should be increased by 20%. However, the table does not include formulas for some gypsum plasterboard cladding types. In these cases, the failure time is taken equal with the charring time, but it can be unclear as to whether the value should be increased by 20% or not. Also, it is unclear, how to calculate the failure times of fire protection on beams. There are separate formulas for walls and floors. When adapting those formulas to beams, should the lower side be considered as floor and the vertical sides as walls? When to apply permission that $t_{f,pr}=t_{ch}$ (that is valid for walls)?

Second, the user of EN 1995-1-2:2020 has to identify whether the bond line integrity in glulam timber members is maintained or not during fire exposure. Based on that, there are different calculation models for glulam members.

Third, in both versions there is no reference to which strength property should be used when calculating the stability of a member. There can be a temptation to use the strength property for fire temperature design and stiffness property for normal temperature design, but they should be taken either for fire temperature or for normal temperature. As the ratio of strength and stiffness is the same for both fire and normal temperature design, it does not matter which one is chosen.

Furthermore, the depth of the zero-strength layer for linear members exposed to multiple stresses is unclear. For example, if member is both compressed and bended.

Finally, EN 1995-1-2:2020 can be confusing for the user at first, as it more thorough and contains more formulas than EN 1995-1-2:2004. However, after familiarising with it and using it, it is more logical and user-friendly than EN 1995-1-2:2004 was.

SUMMARY

As the Eurocode 5 part 1-2 is being revised, there is a necessity to evaluate the proposed changes. In this thesis, fire resistance after 30, 60 and 90 minutes was calculated on 4 beams and 3 columns with 3 different protection systems. The calculations were performed according to EN 1995-1-2:2004 and EN 1995-1-2:2020. The results were compared to each other and to the test results. In addition, the user experience and the changes among calculation models were evaluated.

From analysis of the calculation models, the following conclusions could be drawn:

- the most significant changes are in the start time of charring, the failure time of protection and the depth of the zero-strength layer;
- the failure time of gypsum plasterboard type F is added.

During the analysis of the calculation results, the following points were noted:

- the fire resistance of beams has decreased in fire durations longer than 30 minutes, but they have increased for beams with one layer of GtA 12,5 after 30 minutes of fire and for beams with one layer of GtF 15 throughout fire exposure;
- the change in the fire resistance of beams is due to t_{ch}, t_f and d_0;
- the fire resistance of columns has decreased in all cases, because of a significantly deeper zero-strength layer.

The comparison of fire resistance in tests and calculation models gave the following results:

- the results of calculations are close to the test results;
- changing the depth of the zero-strength layer on beams to 10 mm would give more conservative results.
- the increased depth of the zero-strength layer gave the calculations a result that is closer to the tested column, but one column is not enough to decide the necessity of the increase.

EN 1995-1-2:2020 was evaluated to be more user-friendly than EN 1995-1-2:2004, although some improvements can be added.

Further research and more data are needed to compare the calculations with the tested columns. Furthermore, linear interpolation of d_0 in EN 1995-1-2:2020 and permission 3.4.2 (3) in EN 1995-1-2:2004 were not applied in this thesis.

KOKKUVÕTE

Kuna hetkel kirjutatakse Eurokoodeks 5 osa 1-2st uut versiooni, siis on oluline hinnata planeeritud muudatusi. Selles töös on arvutatud kolme erineva kattega nelja tala ja kolme posti kandevõimed 30-, 60- ja 90-minutise tule järel. Arvutused on tehtud EN 1995-1-2:2004 ja EN 1995-1-2:2020 põhjal. Arvutustulemused võrreldi nii omavahel kui ka katsetulemustega. Lisaks sellele hinnati kasutajakogemust.

EN 1995-1-2:2004 ja EN 1995-1-2:2020 arvutusmudelite analüüsis selgus järgnev:

- kõige suuremad muutused on söestumise algusajas, tõrketekkeajas, ja nulltugevusega kihi paksuses;
- lisatud on F tüüpi kipsplaadi tõrketekkeaeg.

Arvutustulemuste võrdluses olid järgnevad tulemused:

- liimpuittalade tulepüsivus on vähenenud pikema, kui 30-minutilise, tule puhul, aga kasvanud ühe kihi A 30-minutilise tule järel tüüpi ja ühe kihi F tüüpi kipsplaadiga kaetud liimpuittaladel kogu tulekahju vältel;
- liimpuittalade tulepüsivuse erinevus tuleneb söestumise algusaja, tõrketekkeaja, ja nulltugevusega kihi paksuse erinevustest arvutusmudelites;
- liimpuitpostide tulepüsivus on vähenenud kõikidel uuritud juhtudel, kuna koormust mitte vastu võtev kiht on oluliselt paksenenud.

Arvutustulemusi võrreldi katsetulemustega. Võrdluses selgus järgnev:

- arvutustulemused on ligilähedased katsetulemustele;
- võttes liimpuittaladel nulltugevusega kihi paksuseks 10mm, on saadud tulemused rohkem tagavara kasuks;
- suurendades nulltugevusega kihi paksust liimpuitpostil, on arvutustulemus lähedasem testpostile, kuid ühe posti vaatlus ei ole piisav alus järelduste tegemiseks.

Kasutaja kogemuse hindamisel selgus, et EN 1995-1-2:2020 on kasutajasõbralikum kui EN 1995-1-2:2004.

Edasine uurimustöö on vajalik, et hinnata arvutustulemusi tules katsetatud postidega. Lisaks ei kasutatud selles töös lineaarset interpoleerimist EN 1995-1-2:2020 põhjal d_0 arvutamisel ning EN 1995-1-2:2004 põhjal tehtud arvutustes luba 3.4.2 (3).

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APPENDICES

Appendix 1 Calculations of the strength parameters according to 2004 version of Eurocode 5

Table 3.x Materials used in this research and their characteristic values of strength properties for normal temperature

Materials	Design compressive strength along the grain for normal temperature	Design bending strength for normal temperature
GL24c	Is not used in this research	$f_{m,g,k} = 24{,}0\ \frac{N}{mm^2}$
GL24h	$f_{c,0,g,k} = 21{,}5\frac{N}{mm^2}$	Is not used in this research

$\gamma_{M,fi} = 1{,}0$

$k_{fi} = 1{,}15$

$k_{\text{mod,fi}} = 1{,}0$

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

$$f_{20} = k_{fi}f_k$$

Table 4.x Materials used in this research and their characteristic values of strength properties for fire exposure

Materials	Design compressive strength along the grain for fire exposure		Design bending strength for fire exposure	
	The 20% fractile of strength	The fire design value of strength	The 20% fractile of strength	The fire design value of strength
GL24c	Is not used in this research		$f_{20} = 1{,}15 * 24{,}0 = = 27{,}6\frac{N}{mm^2}$	$f_{d,fi} = 1{,}0\frac{27{,}6}{1{,}0} = = 27{,}6\frac{N}{mm^2}$
GL24h	$f_{20} = 1{,}15 * 21{,}5 = = 24{,}75\frac{N}{mm^2}$	$f_{d,fi} = 1{,}0\frac{24{,}75}{1{,}0} = = 24{,}75\frac{N}{mm^2}$	Is not used in this research	

Appendix 2 Calculations of unprotected glulam beam according to 2004 version of Eurocode 5

height	h = 200 mm
width	b = 80 mm
material	GL24c
time	30 min
sides open to fire	3
protection	none

$d_{char,n} = \beta_n t$ $\quad$ $d_{char,n} = 0{,}7 * 30 = 21\ mm$

$d_{ef} = d_{char,n} + k_0 d_0$ $\quad$ $d_{ef} = 21 + 1 * 7 = 28\ mm$

$b_{fi} = b - 2d_{ef}$ $\quad$ $b_{fi} = 80 - 2 * 28 = 24\ mm$

$h_{fi} = h - d_{ef}$ $\quad$ $h_{fi} = 200 - 28 = 172\ mm$

$W_{ef} = \frac{b_{fi} {h_{fi}}^2}{6}$ $\quad$ $W_{ef} = \frac{24*172^2}{6} = 118336\ mm^3$

$M_{max,fi} = W_{ef} f_{d,fi} 10^{-6}$ $\quad$ $M_{max,fi} = 118336 * 27{,}6 * \ 10^{-6} = 3{,}2\ kNm$

Table. Glulam beam without protective layer according to 2004 version of Eurocode 5 after 30 minutes of fire

Cross-section / mm x mm	80x200	200x400	200x600	200x1000
Protective layer	none	none	none	none
Result / kNm	**3.2**	**91.6**	**216.7**	**625.8**
Required time / min	30	30	30	30
Strength class	GL24c	GL24c	GL24c	GL24c
b / mm	80	200	200	200
h / mm	200	400	600	1000
$\gamma_{M,fi}$	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	24	24	24
$k_{mod,fi}$	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	27.6	27.6	27.6
β_n	0.7	0.7	0.7	0.7
$d_{char,n}$ / mm	21	21	21	21
k_0	1	1	1	1
d_0 / mm	7	7	7	7
d_{ef} / mm	28	28	28	28
b_{fi} / mm	24	144	144	144
h_{fi} / mm	172	372	572	972
W_{fi} / mm^3	118336	3321216	7852416	22674816
$M_{max,fi}$ / kNm	3.2	91.6	216.7	625.8

Table. Glulam beam without protective layer according to 2004 version of Eurocode 5 after 60 minutes of fire

Cross-section / mm x mm	80x200	200x400	200x600	200x1000
Protective layer	none	none	none	none
Result / kNm	**0**	**57.8**	**142.4**	**424.3**
Required time / min	60	60	60	60
Strength class	GL24c	GL24c	GL24c	GL24c
b / mm	80	200	200	200
h / mm	200	400	600	1000
$\gamma_{M,fi}$	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	24	24	24
$k_{mod,fi}$	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	27.6	27.6	27.6
β_n	0.7	0.7	0.7	0.7
$d_{char,n}$ / mm	42	42	42	42
k_0	1	1	1	1
d_0 / mm	7	7	7	7
d_{ef} / mm	49	49	49	49
b_{fi} / mm	0	102	102	102
h_{fi} / mm	151	351	551	951
W_{fi} / mm^3	0	2094417	5161217	15374817
$M_{max,fi}$ / kNm	0	57.8	142.4	424.3

Table. Glulam beam without protective layer according to 2004 version of Eurocode 5 after 90 minutes of fire

Cross-section / mm x mm	80x200	200x400	200x600	200x1000
Protective layer	none	none	none	none
Result / kNm	**0**	**30**	**77.5**	**238.7**
Required time / min	90	90	90	90
Strength class	GL24c	GL24c	GL24c	GL24c
b / mm	80	200	200	200
h / mm	200	400	600	1000
$\gamma_{M,fi}$	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	24	24	24
$k_{mod,fi}$	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	27.6	27.6	27.6
β_n	0.7	0.7	0.7	0.7
$d_{char,n}$ / mm	63	63	63	63
k_0	1	1	1	1
d_0 / mm	7	7	7	7
d_{ef} / mm	70	70	70	70
b_{fi} / mm	0	60	60	60
h_{fi} / mm	130	330	530	930
W_{fi} / mm^3	0	1089000	2809000	8649000
$M_{max,fi}$ / kNm	0	30	77.5	238.7

Appendix 3 Calculations of glulam beam with one layer of GtA 12,5 according to 2004 version of Eurocode 5

height	h = 200 mm
width	b = 80 mm
material	GL24c
time	30 min
sides open to fire	3
protection	GtA 12,5
fire protective panel thickness	h_p = 12,5 mm

$t_{ch} = 2{,}8\, h_p - 14$ $\qquad t_{ch} = 2{,}8 * 12{,}5 - 14 = 21\, min$

$t_f = t_{ch}$ $\qquad t_f = 21\, min$

$k_3 = 2$

$t_a = min\begin{cases} 2t_f \\ \dfrac{25}{k_3\beta_n} + t_f \end{cases}$ $\qquad t_a = min\begin{cases} 2 * 21 = 42\, min \\ \dfrac{25}{2 * 0{,}7} + 21 = 38{,}8\, min \end{cases} = 38{,}8\, min > t = 30\, min$

$d_{char,n,t_f} = (t_f - t_{ch})k_2\beta_n$ $\qquad d_{char,n,t_f} = (21 - 21)k_2 * 0{,}7 = 0\, mm$

$d_{char,n,t_a} = d_{char,n,t_f} + (t_a - t_f)\, k_3\beta_n$ $\qquad d_{char,n,t_a} = 0 + (38{,}8 - 21)2 * 0{,}7 = 25\, mm$

$d_{char,n,t} = d_{char,n,t_f} + (t - t_{ch})k_3\beta_n$ $\qquad d_{char,n,t} = 0 + (30 - 21)2 * 0{,}7 = 12{,}6\, mm$

$d_{ef} = d_{char,n,t} + k_0 d_0$ $\qquad d_{ef} = 12{,}6 + 1 * 7 = 19{,}6\, mm$

$b_{fi} = b - 2d_{ef}$ $\qquad b_{fi} = 80 - 2 * 19{,}6 = 40{,}8\, mm$

$h_{fi} = h - d_{ef}$ $\qquad h_{fi} = 200 - 19{,}6 = 180{,}4\, mm$

$W_{ef} = \dfrac{b_{fi}{h_{fi}}^2}{6}$ $\qquad W_{ef} = \dfrac{40{,}8 * 180{,}4^2}{6} = 221300{,}3\, mm^3$

$M_{max,fi} = W_{ef} f_{d,fi} 10^{-6}$ $\qquad M_{max,fi} = 221300{,}3 * 27{,}6 * 10^{-6} = 6{,}1\, kNm$

Table. Glulam beam with one layer of GtA 12,5 according to 2004 version of Eurocode 5 after 30 minutes of fire

Cross-section / mm x mm	80x200	200x400	200x600	200x1000
Protective layer	GtA12,5	GtA12,5	GtA12,5	GtA12,5
Result / kNm	**6.1**	**107**	**249.1**	**710.9**
Required time / min	30	30	30	30
Strength class	GL24c	GL24c	GL24c	GL24c
b / mm	80	200	200	200
h / mm	200	400	600	1000
$\gamma_{M,fi}$	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	24	24	24
$k_{mod,fi}$	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	27.6	27.6	27.6
h_p /mm	12.5	12.5	12.5	12.5
k_2	-	-	-	-
k_3	2	2	2	2
t_{ch} / min	21	21	21	21
t_f / min	21	21	21	21
β_n	0.7	0.7	0.7	0.7
t_a / min	38.85714	38.85714	38.85714	38.85714
β_{n*k2}	-	-	-	-
β_{n*k3}	1.4	1.4	1.4	1.4
$d_{char,n\ tf}$ / mm	0	0	0	0
$d_{char,n\ ta}$ / mm	25	25	25	25
$d_{char,n\ t}$ / mm	12.6	12.6	12.6	12.6
k_0	1	1	1	1
d_0 / mm	7	7	7	7
d_{ef} / mm	19.6	19.6	19.6	19.6
b_{fi} / mm	40.8	160.8	160.8	160.8
h_{fi} / mm	180.4	380.4	580.4	980.4
W_{fi} / mm^3	221300.3	3878072	9027960	25759736
$M_{max,fi}$ / kNm	6.1	107	249.1	710.9

Table. Glulam beam with one layer of GtA 12,5 according to 2004 version of Eurocode 5 after 60 minutes of fire

Cross-section / mm x mm	80x200	200x400	200x600	200x1000
Protective layer	GtA12,5	GtA12,5	GtA12,5	GtA12,5
Result / kNm	**0**	**61**	**149.7**	**444.7**
Required time / min	60	60	60	60
Strength class	GL24c	GL24c	GL24c	GL24c
b / mm	80	200	200	200
h / mm	200	400	600	1000
$\gamma_{M,fi}$	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	24	24	24
$k_{mod,fi}$	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	27.6	27.6	27.6
h_p /mm	12.5	12.5	12.5	12.5
k_2	-	-	-	-
k_3	2	2	2	2
t_{ch} / min	21	21	21	21
t_f / min	21	21	21	21
β_n	0.7	0.7	0.7	0.7
t_a / min	38.85714	38.85714	38.85714	38.85714
β_{n*k2}	-	-	-	-
β_{n*k3}	1.4	1.4	1.4	1.4
$d_{char,n\ tf}$ / mm	0	0	0	0
$d_{char,n\ ta}$ / mm	25	25	25	25
$d_{char,n\ t}$ / mm	39.8	39.8	39.8	39.8
k_0	1	1	1	1
d_0 / mm	7	7	7	7
d_{ef} / mm	46.8	46.8	46.8	46.8
b_{fi} / mm	0	106.4	106.4	106.4
h_{fi} / mm	153.2	353.2	553.2	953.2
W_{fi} / mm^3	0	2212238	5426936	16112334
$M_{max,fi}$ / kNm	0	61	149.7	444.7

Table. Glulam beam with one layer of GtA 12,5 according to 2004 version of Eurocode 5 after 90 minutes of fire

Cross-section / mm x mm	80x200	200x400	200x600	200x1000
Protective layer	GtA12,5	GtA12,5	GtA12,5	GtA12,5
Result / kNm	**0**	**32.6**	**83.9**	**257.4**
Required time / min	90	90	90	90
Strength class	GL24c	GL24c	GL24c	GL24c
b / mm	80	200	200	200
h / mm	200	400	600	1000
$\gamma_{M,fi}$	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	24	24	24
$k_{mod,fi}$	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	27.6	27.6	27.6
h_p /mm	12.5	12.5	12.5	12.5
k_2	-	-	-	-
k_3	2	2	2	2
t_{ch} / min	21	21	21	21
t_f / min	21	21	21	21
β_n	0.7	0.7	0.7	0.7
t_a / min	38.85714	38.85714	38.85714	38.85714
β_{n*k2}	-	-	-	-
β_{n*k3}	1.4	1.4	1.4	1.4
$d_{char,n\ tf}$ / mm	0	0	0	0
$d_{char,n\ ta}$ / mm	25	25	25	25
$d_{char,n\ t}$ / mm	60.8	60.8	60.8	60.8
k_0	1	1	1	1
d_0 / mm	7	7	7	7
d_{ef} / mm	67.8	67.8	67.8	67.8
b_{fi} / mm	0	64.4	64.4	64.4
h_{fi} / mm	132.2	332.2	532.2	932.2
W_{fi} / mm^3	0	1184497	3040075	9327233
$M_{max,fi}$ / kNm	0	32.6	83.9	257.4

Appendix 4 Calculations of glulam beam with one layer of GtF 15 according to 2004 version of Eurocode 5

height	h = 200 mm
width	b = 80 mm
material	GL24c
time	30 min
sides open to fire	3
protection	GtF 15
fire protective panel thickness	h_p = 15 mm

$t_f = h_p + 10$ $\quad$ $t_f = 15 + 10 = 25\,min < t = 30\,min$

$t_{ch} = 2{,}8\,h_p - 14$ $\quad$ $t_{ch} = 2{,}8 * 15 - 14 = 28\,min \leq t_f = 25\,min$

$k_2 = 1 - 0{,}018h_p$ $\quad$ $k_2 = 1 - 0{,}018 * 15 = 0{,}73$

$k_3 = 2$

$$t_a = \frac{25 - (t_f - t_{ch})k_2\beta_n}{k_3\beta_n} + t_f \qquad t_a = \frac{25 - (25 - 25)0{,}73 * 0{,}7}{2 * 0{,}7} + 25 = 42{,}86\,min$$

$d_{char,n,t_f} = (t_f - t_{ch})k_2\beta_n$ $\quad$ $d_{char,n,t_f} = (25 - 25)0{,}73 * 0{,}7 = 0\,mm$

$d_{char,n,t_a} = d_{char,n,t_f} + (t_a - t_f)\,k_3\beta_n$ $\quad$ $d_{char,n,t_a} = 0 + (42{,}5 - 25)2 * 0{,}7 = 25\,mm$

$d_{char,n,t} = d_{char,n,t_f} + (t - t_f)k_3\beta_n$ $\quad$ $d_{char,n,t} = 0 + (30 - 25)2 * 0{,}7 = 7\,mm$

$d_{ef} = d_{char,n,t} + k_0 d_0$ $\quad$ $d_{ef} = 7{,}0 + 1 * 7 = 14{,}0\,mm$

$b_{fi} = b - 2d_{ef}$ $\quad$ $b_{fi} = 80 - 2 * 14 = 52\,mm$

$h_{fi} = h - d_{ef}$ $\quad$ $h_{fi} = 200 - 14 = 186\,mm$

$$W_{ef} = \frac{b_{fi}{h_{fi}}^2}{6} \qquad W_{ef} = \frac{52 * 186^2}{6} = 299832\,mm^3$$

$M_{max,fi} = W_{ef}f_{d,fi}10^{-6}$ $\quad$ $M_{max,fi} = 299832 * 27{,}6 * 10^{-6} = 8{,}2\,kNm$

Table. Glulam beam with one layer of GtF 15 according to 2004 version of Eurocode 5 after 30 minutes of fire

Cross-section / mm x mm	80x200	200x400	200x600	200x1000
Protective layer	GtF15	GtF15	GtF15	GtF15
Result / kNm	**10.8**	**130**	**296.5**	**832.6**
Required time / min	30	30	30	30
Strength class	GL24c	GL24c	GL24c	GL24c
b / mm	80	200	200	200
h / mm	200	400	600	1000
$\gamma M,fi$	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	24	24	24
$k_{mod,fi}$	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	27.6	27.6	27.6
h_p /mm	15	15	15	15
k_2	0.73	0.73	0.73	0.73
k_3	2	2	2	2
t_{ch} / min	28	28	28	28
t_f / min	25	25	25	25
β_n	0.7	0.7	0.7	0.7
t_a / min	42.85714	42.85714	42.85714	42.85714
β_{n*k2}	0.511	0.511	0.511	0.511
β_{n*k3}	1.4	1.4	1.4	1.4
$d_{char,n\ tf}$ / mm	0	0	0	0
$d_{char,n\ ta}$ / mm	25	25	25	25
$d_{char,n\ t}$ / mm	7	7	7	7
k_0	1	1	1	1
d_0 / mm	7	7	7	7
d_{ef} / mm	14	14	14	14
b_{fi} / mm	52	172	172	172
h_{fi} / mm	186	386	586	986
W_{fi} / mm^3	299832	4271219	9844019	27869619
$M_{max,fi}$ / kNm	8.2	117.8	271.6	769.2

Table. Glulam beam with one layer of GtF 15 according to 2004 version of Eurocode 5 after 60 minutes of fire

Cross-section / mm x mm	80x200	200x400	200x600	200x1000
Protective layer	GtF15	GtF15	GtF15	GtF15
Result / kNm	**1.2**	**79.6**	**190.8**	**556.7**
Required time / min	60	60	60	60
Strength class	GL24c	GL24c	GL24c	GL24c
b / mm	80	200	200	200
h / mm	200	400	600	1000
$\gamma_{M,fi}$	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	24	24	24
$k_{mod,fi}$	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	27.6	27.6	27.6
h_p /mm	15	15	15	15
k_2	0.73	0.73	0.73	0.73
k_3	2	2	2	2
t_{ch} / min	28	28	28	28
t_f / min	25	25	25	25
β_n	0.7	0.7	0.7	0.7
t_a / min	42.85714	42.85714	42.85714	42.85714
β_{n*k2}	0.511	0.511	0.511	0.511
β_{n*k3}	1.4	1.4	1.4	1.4
$d_{char,n\ tf}$ / mm	0	0	0	0
$d_{char,n\ ta}$ / mm	25	25	25	25
$d_{char,n\ t}$ / mm	37	37	37	37
k_0	1	1	1	1
d_0 / mm	7	7	7	7
d_{ef} / mm	44	44	44	44
b_{fi} / mm	0	112	112	112
h_{fi} / mm	156	356	556	956
W_{fi} / mm^3	0	2365739	5770539	17060139
$M_{max,fi}$ / kNm	0	65.2	159.2	470.8

Table. Glulam beam with one layer of GtF 15 according to 2004 version of Eurocode 5 after 90 minutes of fire

Cross-section / mm x mm	80x200	200x400	200x600	200x1000
Protective layer	GtF15	GtF15	GtF15	GtF15
Result / kNm	**0**	**47.8**	**119.7**	**360.6**
Required time / min	90	90	90	90
Strength class	GL24c	GL24c	GL24c	GL24c
b / mm	80	200	200	200
h / mm	200	400	600	1000
$\gamma_{M,fi}$	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	24	24	24
$k_{mod,fi}$	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	27.6	27.6	27.6
h_p /mm	15	15	15	15
k_2	0.73	0.73	0.73	0.73
k_3	2	2	2	2
t_{ch} / min	28	28	28	28
t_f / min	25	25	25	25
β_n	0.7	0.7	0.7	0.7
t_a / min	42.85714	42.85714	42.85714	42.85714
β_{n*k2}	0.511	0.511	0.511	0.511
β_{n*k3}	1.4	1.4	1.4	1.4
$d_{char,n\ tf}$ / mm	0	0	0	0
$d_{char,n\ ta}$ / mm	25	25	25	25
$d_{char,n\ t}$ / mm	58	58	58	58
k_0	1	1	1	1
d_0 / mm	7	7	7	7
d_{ef} / mm	65	65	65	65
b_{fi} / mm	0	70	70	70
h_{fi} / mm	135	335	535	935
W_{fi} / mm^3	0	1309292	3339292	10199292
$M_{max,fi}$ / kNm	0	36.1	92.1	281.5

Appendix 5 Calculations of unprotected glulam column according to 2004 version of Eurocode 5

column height	l=3m=3000mm
height	h = 80 mm
width	b = 80 mm
material	GL24h
design compressive strengths along the grain	$f_{c,o,g,k} = 21{,}5 \frac{N}{mm^2}$
the fifth percentile value of the modulus of elasticity	$E_{0,g,05} = 9600$
time	30 min
sides open to fire	4
protection	none

Effective cross-section method

$d_{char,n} = \beta_n t$ $\quad$ $d_{char,n} = 0{,}7 * 30 = 21\,mm$

$d_{ef} = d_{char,n} + k_0 d_0$ $\quad$ $d_{ef} = 21 + 1 * 7 = 28\,mm$

$b_{fi} = b - 2d_{ef}$ $\quad$ $b_{fi} = 80 - 2 * 28 = 24\,mm$

$h_{fi} = h - 2d_{ef}$ $\quad$ $h_{fi} = 80 - 2 * 28 = 24\,mm$

$A_{fi} = b_{fi} h_{fi}$ $\quad$ $A_{fi} = 24 * 24 = 576\,mm^2$

$N_{max,fi} = A_{fi} f_{d,fi} 10^{-3}$ $\quad$ $N_{max,fi} = 576 * 24{,}7 * 10^{-3} = 14{,}2\,kN$

Slenderness

$$I = \frac{b_{fi} {h_{fi}}^3}{12} \qquad I = \frac{24 * 24^3}{12} = 27648\,mm^4$$

$$i = \sqrt{\frac{I}{A_{fi}}} \qquad i = \sqrt{\frac{27648}{576}} = 6{,}9\,mm$$

$$l_0 = \mu l \qquad l_0 = 0{,}7 * 3000 = 2100\,mm$$

$$\lambda_y = \frac{l_0}{i} \qquad \lambda_y = \frac{2100}{6{,}9} = 303{,}1$$

$$\lambda_{rel,y} = \frac{\lambda_y}{\pi} \sqrt{\frac{f_{c,o,g,k}}{E_{0,g,05}}} \qquad \lambda_{rel,y} = \frac{303{,}1}{\pi} \sqrt{\frac{21{,}5}{9600}} = 4{,}57$$

$$\beta_c = 0{,}1$$

$$k_y = 0{,}5\left(1 + \beta_c(\lambda_{rel,y} - 0{,}3) + {\lambda_{rel,y}}^2\right) \qquad k_y = 0{,}5\,(1 + 0{,}1(4{,}57 - 0{,}3) + 4{,}57^2) = 11{,}1$$

$$k_{cy} = \frac{1}{k_y + \sqrt{{k_y}^2 - {\lambda_{rel,y}}^2}} \qquad k_{cy} = \frac{1}{11{,}1 + \sqrt{11{,}1^2 - 4{,}57^2}} = 0{,}047$$

$$\sigma_{c,0,d} = k_{cy} f_{c,o,g,k} \qquad \sigma_{c,0,d} = 0{,}047 * 21{,}5 = 1{,}01 \frac{N}{mm^2}$$

$$N_{max,fi} = A_{fi} \sigma_{c,0,d} 10^{-3} \qquad N_{max,fi} = 576 * 1{,}01 * 10^{-3} = 0{,}581\,kN$$

Table. Glulam column without protective layer according to 2004 version of Eurocode 5 after 30 minutes of fire

Cross-section / mm x mm	80x80	200x200	400x400
Protective layer	none	none	none
Result / kN	**0.5**	**406.1**	**2538.9**
Required time / min	30	30	30
Strength class	GL24h	GL24h	GL24h
L / m	3	3	3
b / mm	80	200	400
h / mm	80	200	400
$\gamma_{M,fi}$	1	1	1
k_{fi}	1.15	1.15	1.15
$f_{c,0,g,k}$ / kN/mm^2	21.5	21.5	21.5
$k_{mod,fi}$	1	1	1
$f_{d,fi}$ / kN/mm^2	24.725	24.725	24.725
β_n / mm/min	0.7	0.7	0.7
$d_{char,n}$ / mm	21	21	21
k_0	1	1	1
d_0 / mm	7	7	7
d_{ef} / mm	28	28	28
b_{fi} / mm	24	144	344
h_{fi} / mm	24	144	344
A_{fi} / mm^2	576	20736	118336
$N_{max,fi}$ / kN	14.2	512.6	2925.8
I / mm4	27648	35831808	1166950741
i / mm	6.92820323	41.5692194	99.3042463
l0 / mm	2100	2100	2100
λy	303.108891	50.5181486	21.147132
E0,05 / kN/mm2	9600	9600	9600
λrel,y	4.5659633	0.76099388	0.31855558
ky	11.1373086	0.81260554	0.55166661
kcy	0.04695798	0.91108712	0.99793961
σc,0,d / kN/mm2	1.0095965	19.5883731	21.4557017
Nmax,fi / kN	0.58152759	406.184504	2538.98191

Table. Glulam column without protective layer according to 2004 version of Eurocode 5 after 60 minutes of fire

Cross-section / mm x mm	80x80	200x200	400x400
Protective layer	none	none	none
Result / kN	**0**	**157.8**	**1946.8**
Required time / min	60	60	60
Strength class	GL24h	GL24h	GL24h
L / m	3	3	3
b / mm	80	200	400
h / mm	80	200	400
$\gamma_{M,fi}$	1	1	1
k_{fi}	1.15	1.15	1.15
$f_{c,0,g,k}$ / kN/mm^2	21.5	21.5	21.5
$k_{mod,fi}$	1	1	1
$f_{d,fi}$ / kN/mm^2	24.725	24.725	24.725
β_n / mm/min	0.7	0.7	0.7
$d_{char,n}$ / mm	42	42	42
k_0	1	1	1
d_0 / mm	7	7	7
d_{ef} / mm	49.00	49	49
b_{fi} / mm	0	102	302
h_{fi} / mm	0	102	302
A_{fi} / mm^2	0	10404	91204
$N_{max,fi}$ / kN	0	257.2	2255
I / mm4	0	9020268	693180801
i / mm	0	29.4448637	87.1798906
l0 / mm	2100	2100	2100
λy	0	71.3197391	24.0881238
E0,05 / kN/mm2	9600	9600	9600
λrel,y	0	1.07434431	0.36285801
ky	0.485	1.11582506	0.56897587
kcy	1.03092784	0.70559769	0.99282086
σc,0,d / kN/mm2	21.5	15.1703504	21.3456486
Nmax,fi / kN	0	157.832326	1946.80853

Table. Glulam column without protective layer according to 2004 version of Eurocode 5 after 90 minutes of fire

Cross-section / mm x mm	80x80	200x200	400x400
Protective layer	none	none	none
Result / kN	**0**	**21.8**	**1432.3**
Required time / min	90	90	90
Strength class	GL24h	GL24h	GL24h
L / m	3	3	3
b / mm	80	200	400
h / mm	80	200	400
$\gamma_{M,fi}$	1	1	1
k_{fi}	1.15	1.15	1.15
$f_{c,0,g,k}$ / kN/mm^2	21.5	21.5	21.5
$k_{mod,fi}$	1	1	1
$f_{d,fi}$ / kN/mm^2	24.725	24.725	24.725
β_n / mm/min	0.7	0.7	0.7
$d_{char,n}$ / mm	63	63	63
k_0	1	1	1
d_0 / mm	7	7	7
d_{ef} / mm	70	70	70
b_{fi} / mm	0	60	260
h_{fi} / mm	0	60	260
A_{fi} / mm^2	0	3600	67600
$N_{max,fi}$ / kN	0	89	1671.4
I / mm4	0	1080000	380813333
i / mm	0	17.3205081	75.055535
l0 / mm	2100	2100	2100
λy	0	121.243557	27.9792823
E0,05 / kN/mm2	9600	9600	9600
λrel,y	0	1.82638532	0.42147354
ky	0.485	2.24416094	0.59489365
kcy	1.03092784	0.2818313	0.98548851
σc,0,d / kN/mm2	21.5	6.05937302	21.188003
Nmax,fi / kN	0	21.8137429	1432.309

Appendix 6 Calculations of glulam column with one layer of GtA 12,5 according to 2004 version of Eurocode 5

column height	l=3m=3000mm
height	h = 80 mm
width	b = 80 mm
material	GL24h
design compressive strengths along the grain	$f_{c,o,g,k} = 21{,}5 \frac{N}{mm^2}$
the fifth percentile value of the modulus of elasticity	$E_{0,g,05} = 9600$
time	30 min
sides open to fire	4
protection	GtA 12,5
fire protective panel thickness	$\mathrm{h_p}$ = 12,5 mm

Effective cross-section method

$t_{ch} = 2{,}8\, h_p - 14$ $\quad$ $t_{ch} = 2{,}8 * 12{,}5 - 14 = 21\, min$

$t_f = t_{ch}$ $\quad$ $t_f = 21\, min$

$k_3 = 2$

$$t_a = min\begin{cases} 2t_f \\ \frac{25}{k_3\beta_n} + t_f \end{cases} \qquad t_a = min\begin{cases} 2 * 21 = 42\, min \\ \frac{25}{2 * 0{,}7} + 21 = 38{,}8\, min \end{cases} = 38{,}8\, min > t = 30\, min$$

$d_{char,n,t_f} = (t_f - t_{ch})k_2\beta_n$ $\quad$ $d_{char,n,t_f} = (21 - 21)k_2 * 0{,}7 = 0\, mm$

$d_{char,n,t_a} = d_{char,n,t_f} + (t_a - t_f)\, k_3\beta_n$ $\quad$ $d_{char,n,t_a} = 0 + (38{,}8 - 21)2 * 0{,}7 = 25\, mm$

$d_{char,n,t} = d_{char,n,t_f} + (t - t_{ch})k_3\beta_n$ $\quad$ $d_{char,n,t} = 0 + (30 - 21)2 * 0{,}7 = 12{,}6\, mm$

$d_{ef} = d_{char,n,t} + k_0 d_0$ $\quad$ $d_{ef} = 12{,}6 + 1 * 7 = 19{,}6\, mm$

$b_{fi} = b - 2d_{ef}$ $\quad$ $b_{fi} = 80 - 2 * 19{,}6 = 40{,}8\, mm$

$h_{fi} = h - 2d_{ef}$ $\quad$ $h_{fi} = 80 - 2 * 19{,}6 = 40{,}8\ mm$

$A_{fi} = b_{fi}h_{fi}$ $\quad$ $A_{fi} = 40{,}8 * 40{,}8 = 1664{,}6\, mm^2$

$N_{max,fi} = A_{fi}f_{d,fi}10^{-3}$ $\quad$ $N_{max,fi} = 1664{,}6 * 24{,}7 * 10^{-3} = 41{,}1\, kN$

Slenderness

$$I = \frac{b_{fi}{h_{fi}}^3}{12} \qquad I = \frac{40{,}8 * 40{,}8^3}{12} = 230919\, mm^4$$

$$i = \sqrt{\frac{I}{A_{fi}}} \qquad i = \sqrt{\frac{230919}{1664{,}6}} = 11{,}8\, mm$$

$$l_0 = \mu l \qquad l_0 = 0{,}7 * 3000 = 2100\,mm$$

$$\lambda_y = \frac{l_0}{i} \qquad \lambda_y = \frac{2100}{11{,}8} = 178{,}3$$

$$\lambda_{rel,y} = \frac{\lambda_y}{\pi}\sqrt{\frac{f_{c,o,g,k}}{E_{0,g,05}}} \qquad \lambda_{rel,y} = \frac{178{,}3}{\pi}\sqrt{\frac{21{,}5}{9600}} = 2{,}69$$

$$\beta_c = 0{,}1$$

$$k_y = 0{,}5\left(1 + \beta_c\left(\lambda_{rel,y} - 0{,}3\right) + {\lambda_{rel,y}}^2\right) \qquad k_y = 0{,}5\,(1 + 0{,}1(2{,}69 - 0{,}3) + 2{,}69^2) = 4{,}23$$

$$k_{cy} = \frac{1}{k_y + \sqrt{{k_y}^2 - {\lambda_{rel,y}}^2}} \qquad k_{cy} = \frac{1}{4{,}23 + \sqrt{4{,}23^2 - 2{,}69^2}} = 0{,}113$$

$$\sigma_{c,0,d} = k_{cy} f_{c,o,g,k} \qquad \sigma_{c,0,d} = 0{,}113 * 21{,}5 = 2{,}87\,\frac{N}{mm^2}$$

$$N_{max,fi} = A_{fi}\sigma_{c,0,d}10^{-3} \qquad N_{max,fi} = 1664{,}6 * 2{,}87 * 10^{-3} = 4{,}78\,kN$$

Table. Glulam column with one layer of GtA 12,5 according to 2004 version of Eurocode 5 after 30 minutes of fire

Cross-section / mm x mm	80x80	200x200	400x400
Protective layer	GtA12,5	GtA12,5	GtA12,5
Result / kN	**4.7**	**520.7**	**2797.6**
Required time / min	30	30	30
Strength class	GL24h	GL24h	GL24h
L / m	3	3	3
b / mm	80	200	400
h / mm	80	200	400
$\gamma_{M,fi}$	1	1	1
k_{fi}	1.15	1.15	1.15
$f_{c,0,g,k}$ / kN/mm^2	21.5	21.5	21.5
$k_{mod,fi}$	1	1	1
$f_{d,fi}$ / kN/mm^2	24.725	24.725	24.725
h_p /mm	12.5	12.5	12.5
k_2	-	-	-
k_3	2	2	2
t_{ch} / min	21	21	21
t_f / min	21	21	21
β_n / mm/min	0.7	0.7	0.7
t_a / min	38.85714	38.85714	38.85714
β_{n*k2} / mm/min			
β_{n*k3} / mm/min	1.4	1.4	1.4
$d_{char,n\ tf}$ / mm	0	0	0
$d_{char,n\ ta}$ / mm	25	25	25
$d_{char,n\ t}$ / mm	12.6	12.6	12.6
k_0	1	1	1
d_0 / mm	7	7	7
d_{ef} / mm	19.6	19.6	19.6
b_{fi} / mm	40.8	160.8	360.8
h_{fi} / mm	40.8	160.8	360.8
A_{fi} / mm^2	1664.64	25856.64	130176.6
$N_{max,fi}$ / kN	41.1	639.3	3218.6
I / mm^4	230918.9	55713819	1.41E+09
i / mm	11.77795	46.41896	104.154
l_0 / mm	2100	2100	2100
λ_y	178.2993	45.24013	20.16245
$E_{0,05}$ / kN/mm^2	9600	9600	9600
$\lambda_{rel,y}$	2.685861	0.681487	0.303723
k_y	4.226217	0.751287	0.54631
k_{cy}	0.133526	0.936746	0.99959
$\sigma_{c,0,d}$ / kN/mm^2	2.8708	20.14003	21.49119
$N_{max,fi}$ / kN	4.778849	520.7536	2797.651

Table. Glulam column with one layer of GtA 12,5 according to 2004 version of Eurocode 5 after 60 minutes of fire

Cross-section / mm x mm	80x80	200x200	400x400
Protective layer	GtA12,5	GtA12,5	GtA12,5
Result / kN	**0**	**180.9**	**2005.1**
Required time / min	60	60	60
Strength class	GL24h	GL24h	GL24h
L / m	3	3	3
b / mm	80	200	400
h / mm	80	200	400
$\gamma_{M,fi}$	1	1	1
k_{fi}	1.15	1.15	1.15
$f_{c,0,g,k}$ / kN/mm^2	21.5	21.5	21.5
$k_{mod,fi}$	1	1	1
$f_{d,fi}$ / kN/mm^2	24.725	24.725	24.725
h_p /mm	12.5	12.5	12.5
k_2	-	-	-
k_3	2	2	2
t_{ch} / min	21	21	21
t_f / min	21	21	21
β_n / mm/min	0.7	0.7	0.7
t_a / min	38.85714	38.85714	38.85714
β_{n*k2} / mm/min			
β_{n*k3} / mm/min	1.4	1.4	1.4
$d_{char,n\ tf}$ / mm	0	0	0
$d_{char,n\ ta}$ / mm	25	25	25
$d_{char,n\ t}$ / mm	39.8	39.8	39.8
k_0	1	1	1
d_0 / mm	7	7	7
d_{ef} / mm	46.8	46.80	46.8
b_{fi} / mm	0	106.4	306.4
h_{fi} / mm	0	106.4	306.4
A_{fi} / mm^2	0	11320.96	93880.96
$N_{max,fi}$ / kN	0	279.9	2321.2
I / mm^4	0	10680345	7.34E+08
i / mm	0	30.71503	88.45006
l_0 / mm	2100	2100	2100
λ_y	0	68.37043	23.74221
$E_{0,05}$ / kN/mm^2	9600	9600	9600
$\lambda_{rel,y}$	0	1.029917	0.357647
k_y	0.485	1.06686	0.566838
k_{cy}	1.030928	0.743395	0.993439
$\sigma_{c,0,d}$ / kN/mm^2	21.5	15.983	21.35895
$N_{max,fi}$ / kN	0	180.9429	2005.199

Table. Glulam column with one layer of GtA 12,5 according to 2004 version of Eurocode 5 after 90 minutes of fire

Cross-section / mm x mm	80x80	200x200	400x400
Protective layer	GtA12,5	GtA12,5	GtA12,5
Result / kN	**0**	**28.7**	**1482.5**
Required time / min	90	90	90
Strength class	GL24h	GL24h	GL24h
L / m	3	3	3
b / mm	80	200	400
h / mm	80	200	400
$\gamma_{M,fi}$	1	1	1
k_{fi}	1.15	1.15	1.15
$f_{c,0,g,k}$ / kN/mm^2	21.5	21.5	21.5
$k_{mod,fi}$	1	1	1
$f_{d,fi}$ / kN/mm^2	24.725	24.725	24.725
h_p /mm	12.5	12.5	12.5
k_2	-	-	-
k_3	2	2	2
t_{ch} / min	21	21	21
t_f / min	21	21	21
β_n / mm/min	0.7	0.7	0.7
t_a / min	38.85714	38.85714	38.85714
β_{n*k2} / mm/min			
β_{n*k3} / mm/min	1.4	1.4	1.4
$d_{char,n\ tf}$ / mm	0	0	0
$d_{char,n\ ta}$ / mm	25	25	25
$d_{char,n\ t}$ / mm	60.8	60.8	60.8
k_0	1	1	1
d_0 / mm	7	7	7
d_{ef} / mm	67.8	67.8	67.8
b_{fi} / mm	0	64.4	264.4
h_{fi} / mm	0	64.4	264.4
A_{fi} / mm^2	0	4147.36	69907.36
$N_{max,fi}$ / kN	0	102.5	1728.4
I / mm^4	0	1433383	4.07E+08
i / mm	0	18.59068	76.32571
l_0 / mm	2100	2100	2100
λ_y	0	112.9598	27.51367
$E_{0,05}$ / kN/mm^2	9600	9600	9600
$\lambda_{rel,y}$	0	1.701601	0.41446
k_y	0.485	2.017803	0.591611
k_{cy}	1.030928	0.322344	0.986406
$\sigma_{c,0,d}$ / kN/mm^2	21.5	6.930392	21.20774
$N_{max,fi}$ / kN	0	28.74283	1482.577

Appendix 7 Calculations of glulam column with one layer of GtF 15 according to 2004 version of Eurocode 5

column height	l=3m=3000mm
height	h = 80 mm
width	b = 80 mm
material	GL24h
design compressive strengths along the grain	$f_{c,o,g,k} = 21{,}5 \frac{N}{mm^2}$
the fifth percentile value of the modulus of elasticity	$E_{0,g,05} = 9600$
time	30 min
sides open to fire	4
protection	GtF 15
fire protective panel thickness	$\mathrm{h_p}$ = 15 mm

Effective cross-section method

$t_{ch} = 2{,}8\,h_p - 14$ $\quad$ $t_{ch} = 2{,}8 * 15 - 14 = 28\,min$

$t_f = 4{,}5 h_p - 24$ $\quad$ $t_f = 4{,}5 * 15 - 24 = 43{,}5\,min > t = 30\,min$

$k_2 = 1 - 0{,}018 h_p$ $\quad$ $k_2 = 1 - 0{,}018 * 15 = 0{,}73$

$k_3 = 2$

$$t_a = \frac{25 - (t_f - t_{ch})k_2\beta_n}{k_3\beta_n} + t_f \qquad t_a = \frac{25 - (43{,}5 - 28)0{,}73 * 0{,}7}{2 * 0{,}7} + 43{,}5 = 55{,}7\,min$$

$d_{char,n,t_f} = (t_f - t_{ch})k_2\beta_n$ $\quad$ $d_{char,n,t_f} = (43{,}5 - 28)0{,}73 * 0{,}7 = 7{,}9\,mm$

$d_{char,n,t_a} = d_{char,n,t_f} + (t_a - t_f)\,k_3\beta_n$ $\quad$ $d_{char,n,t_a} = 7{,}9 + (55{,}7 - 43{,}5)2 * 0{,}7 = 25\,mm$

$d_{char,n,t} = d_{char,n,t_f} + (t - t_{ch})k_2\beta_n$ $\quad$ $d_{char,n,t} = 0 + (30 - 28)0{,}73 * 0{,}7 = 1{,}0\,mm$

$d_{ef} = d_{char,n,t} + k_0 d_0$ $\quad$ $d_{ef} = 1{,}0 + 1 * 7 = 8{,}0\,mm$

$b_{fi} = b - 2d_{ef}$ $\quad$ $b_{fi} = 80 - 2 * 8 = 64{,}0\,mm$

$h_{fi} = h - d_{ef}$ $\quad$ $h_{fi} = 80 - 2 * 8 = 64{,}0\,mm$

$A_{fi} = b_{fi}h_{fi}$ $\quad$ $A_{fi} = 64{,}0 * 64{,}0 = 4090{,}4\,mm^2$

$N_{max,fi} = A_{fi}f_{d,fi}10^{-3}$ $\quad$ $N_{max,fi} = 4090{,}4 * 24{,}7 * 10^{-3} = 101{,}1\,kN$

Slenderness

$$I = \frac{b_{fi}{h_{fi}}^3}{12} \qquad I = \frac{64{,}0 * 64{,}0^3}{12} = 1394261 mm^4$$

$$i = \sqrt{\frac{I}{A_{fi}}} \qquad i = \sqrt{\frac{1394261}{4090{,}4}} = 18{,}5\,mm$$

$l_0 = \mu l$ $\qquad$ $l_0 = 0{,}7 * 3000 = 2100\,mm$

$\lambda_y = \frac{l_0}{i}$ $\qquad$ $\lambda_y = \frac{2100}{18{,}5} = 113{,}7$

$\lambda_{rel,y} = \frac{\lambda_y}{\pi}\sqrt{\frac{f_{c,o,g,k}}{E_{0,g,05}}}$ $\qquad$ $\lambda_{rel,y} = \frac{113{,}7}{\pi}\sqrt{\frac{21{,}5}{9600}} = 1{,}71$

$\beta_c = 0{,}1$

$k_y = 0{,}5\left(1 + \beta_c\left(\lambda_{rel,y} - 0{,}3\right) + {\lambda_{rel,y}}^2\right)$ $\qquad$ $k_y = 0{,}5\,(1 + 0{,}1(1{,}71 - 0{,}3) + 1{,}71^2) = 2{,}04$

$k_{cy} = \frac{1}{k_y + \sqrt{{k_y}^2 - {\lambda_{rel,y}}^2}}$ $\qquad$ $k_{cy} = \frac{1}{2{,}04 + \sqrt{2{,}04^2 - 1{,}71^2}} = 0{,}318$

$\sigma_{c,0,d} = k_{cy} f_{c,o,g,k}$ $\qquad$ $\sigma_{c,0,d} = 0{,}318 * 21{,}5 = 21{,}49\frac{N}{mm^2}$

$N_{max,fi} = A_{fi}\sigma_{c,0,d}10^{-3}$ $\qquad$ $N_{max,fi} = 4090{,}4 * 21{,}49 * 10^{-3} = 28{,}0\,kN$

Table. Glulam column with one layer of GtF 15 according to 2004 version of Eurocode 5 after 30 minutes of fire

Cross-section / mm x mm	80x80	200x200	400x400
Protective layer	GtF15	GtF15	GtF15
Result / kNm	**27.9**	**696.3**	**3169.5**
Required time / min	30	30	30
Strength class	GL24h	GL24h	GL24h
L / m	3	3	3
b / mm	80	200	400
h / mm	80	200	400
$\gamma_{M,fi}$	1	1	1
k_{fi}	1.15	1.15	1.15
$f_{c,0,g,k}$ / kN/mm^2	21.5	21.5	21.5
$k_{mod,fi}$	1	1	1
$f_{d,fi}$ / kN/mm^2	24.725	24.725	24.725
h_p /mm	15	15	15
k_2	0.73	0.73	0.73
k_3	2	2	2
t_{ch} / min	28	28	28
t_f / min	43.5	43.5	43.5
β_n / mm/min	0.7	0.7	0.7
t_a / min	55.69964	55.69964	55.69964
β_{n*k2} / mm/min	0.511	0.511	0.511
β_{n*k3} / mm/min	1.4	1.4	1.4
$d_{char,n\ tf}$ / mm	7.9205	7.9205	7.9205
$d_{char,n\ ta}$ / mm	25	25	25
$d_{char,n\ t}$ / mm	1.022	1.022	1.022
k_0	1	1	1
d_0 / mm	7	7	7
d_{ef} / mm	8.022	8.022	8.022
b_{fi} / mm	63.956	183.956	383.956
h_{fi} / mm	63.956	183.956	383.956
A_{fi} / mm^2	4090.37	33839.81	147422.2
$N_{max,fi}$ / kN	101.1	836.6	3645
I / mm^4	1394261	95427728	1.81E+09
i / mm	18.46251	53.10352	110.8385
l_0 / mm	2100	2100	2100
λ_y	113.744	39.5454	18.94648
$E_{0,05}$ / kN/mm^2	9600	9600	9600
$\lambda_{rel,y}$	1.713414	0.595703	0.285405
k_y	2.038565	0.692216	0.539998
k_{cy}	0.318159	0.957139	1.001592
$\sigma_{c,0,d}$ / kN/mm^2	6.84042	20.5785	21.5
$N_{max,fi}$ / kN	27.97985	696.3724	3169.578

Table. Glulam column with one layer of GtF 15 according to 2004 version of Eurocode 5 after 60 minutes of fire

Cross-section / mm x mm	80x80	200x200	400x400
Protective layer	GtF15	GtF15	GtF15
Result / kNm	**0**	**317.6**	**2332.6**
Required time / min	60	60	60
Strength class	GL24h	GL24h	GL24h
L / m	3	3	3
b / mm	80	200	400
h / mm	80	200	400
$\gamma_{M,fi}$	1	1	1
k_{fi}	1.15	1.15	1.15
$f_{c,0,g,k}$ / kN/mm^2	21.5	21.5	21.5
$k_{mod,fi}$	1	1	1
$f_{d,fi}$ / kN/mm^2	24.725	24.725	24.725
h_p /mm	15	15	15
k_2	0.73	0.73	0.73
k_3	2	2	2
t_{ch} / min	28	28	28
t_f / min	43.5	43.5	43.5
β_n / mm/min	0.7	0.7	0.7
t_a / min	55.69964	55.69964	55.69964
β_{n*k2} / mm/min	0.511	0.511	0.511
β_{n*k3} / mm/min	1.4	1.4	1.4
$d_{char,n\ tf}$ / mm	7.9205	7.9205	7.9205
$d_{char,n\ ta}$ / mm	25	25	25
$d_{char,n\ t}$ / mm	28.01025	28.01025	28.01025
k_0	1	1	1
d_0 / mm	7	7	7
d_{ef} / mm	35.01025	35.01025	35.01025
b_{fi} / mm	9.9795	129.9795	329.9795
h_{fi} / mm	9.9795	129.9795	329.9795
A_{fi} / mm^2	99.59042	16894.67	108886.5
$N_{max,fi}$ / kN	2.4	417.7	2692.2
I / mm^4	826.521	23785824	9.88E+08
i / mm	2.880834	37.52185	95.25688
l_0 / mm	2100	2100	2100
λ_y	728.9557	55.96739	22.04565
$E_{0,05}$ / kN/mm^2	9600	9600	9600
$\lambda_{rel,y}$	10.98082	0.84308	0.332091
k_y	61.32327	0.882546	0.556747
k_{cy}	0.00822	0.874499	0.996408
$\sigma_{c,0,d}$ / kN/mm^2	0.176729	18.80172	21.42277
$N_{max,fi}$ / kN	0.0176	317.6489	2332.649

Table. Glulam column with one layer of GtF 15 according to 2004 version of Eurocode 5 after 90 minutes of fire

Cross-section / mm x mm	80x80	200x200	400x400
Protective layer	GtF15	GtF15	GtF15
Result / kNm	**0**	**94**	**1766.4**
Required time / min	90	90	90
Strength class	GL24h	GL24h	GL24h
L / m	3	3	3
b / mm	80	200	400
h / mm	80	200	400
γM,fi	1	1	1
kfi	1.15	1.15	1.15
fc,0,g,k / kN/mm2	21.5	21.5	21.5
kmod,fi	1	1	1
fd,fi / kN/mm2	24.725	24.725	24.725
hp /mm	15	15	15
k2	0.73	0.73	0.73
k3	2	2	2
tch / min	28	28	28
tf / min	43.5	43.5	43.5
βn / mm/min	0.7	0.7	0.7
ta / min	55.69964	55.69964	55.69964
βn*k2 / mm/min	0.511	0.511	0.511
βn*k3 / mm/min	1.4	1.4	1.4
dchar,n tf / mm	7.9205	7.9205	7.9205
dchar,n ta / mm	25	25	25
dchar,n t / mm	49.01025	49.01025	49.01025
k0	1	1	1
d0 / mm	7	7	7
def / mm	56.01025	56.01025	56.01025
bfi / mm	0	87.9795	287.9795
hfi / mm	0	87.9795	287.9795
Afi / mm2	0	7740.392	82932.19
Nmax,fi / kN	0	191.3	2050.4
I / mm4	0	4992806	5.73E+08
i / mm	0	25.39749	83.13252
l0 / mm	2100	2100	2100
λy	0	82.68532	25.26087
E0,05 / kN/mm2	9600	9600	9600
λrel,y	0	1.245553	0.380524
ky	0.485	1.322979	0.576425
kcy	1.030928	0.565314	0.990687
σc,0,d / kN/mm2	21.5	12.15426	21.29976
Nmax,fi / kN	0	94.07872	1766.436

Appendix 8 Calculations of the strength parameters according to 2020 version of Eurocode 5

Table 4.x Materials used in this research and their characteristic values of strength properties for normal temperature

Materials	Design compressive strength along the grain for normal temperature	Design bending strength for normal temperature
GL24c	Is not used in this research	$f_{m,g,k} = 24,0\ \frac{N}{mm^2}$
GL24h	$f_{c,0,g,k} = 21,5\frac{N}{mm^2}$	Is not used in this research

$\gamma_{M,fi} = 1,0$

$k_{fi} = 1,15$

$k_{\Theta} = 1,0$

$$f_{d,fi} = \frac{k_{\Theta} k_{fi} f_{\mathrm{k}}}{\gamma_{M,fi}}$$

Table 4.x Materials used in this research and their characteristic values of strength properties for fire exposure

Materials	Design compressive strength along the grain for fire exposure	Design bending strength for fire exposure
GL24c	Is not used in this research	$f_{d,fi} = \frac{1,0 * 1,15 * 24}{1,0} = 27,6\frac{N}{mm^2}$
GL24h	$f_{d,fi} = \frac{1,0 * 1,15 * 21,5}{1,0} = 24,7\frac{N}{mm^2}$	Is not used in this research

Appendix 9 Calculations of unprotected glulam beam according to 2020 version of Eurocode 5

height	h = 200 mm
width	b = 80 mm
material	GL24c
design fire strength	$f_{d,fi} = 27{,}6 \frac{N}{mm^2}$
time	30 min
sides open to fire	3
protection	none

$k_{gd} = \begin{cases} 1{,}0 \\ 2{,}0 \end{cases}$ $k_{gd} = 1{,}0$

$k_n = \begin{cases} 1{,}23 \\ 1{,}08 \end{cases}$ $k_n = 1{,}08$

$\beta_n = \prod_{k_i} k_i \, \beta_0$ $\beta_n = 1{,}0 * 1{,}08 * 0{,}65 = 0{,}702\, mm/min$

$d_{char,n} = \beta_n t$ $d_{char,n} = 0{,}70 * 30 = 21{,}1\, mm$

$d_{ef} = d_{char,n} + d_0$ $d_{ef} = 21{,}1 + 7 = 28{,}1\, mm$

$b_{ef} = b - k_{sides} d_{ef}$ $b_{ef} = 80 - 2 * 28{,}1 = 23{,}8\, mm$

$h_{ef} = h - k_{sides} d_{ef}$ $h_{ef} = 200 - 1 * 28{,}1 = 171{,}9\, mm$

$W_{ef} = \frac{b_{ef} {h_{ef}}^2}{6}$ $W_{ef} = \frac{23{,}8 * 171{,}9^2}{6} = 117662\, mm^3$

$M_{max,fi} = W_{ef} f_{d,fi} 10^{-6}$ $M_{max,fi} = 117662 * 27{,}6 * 10^{-6} = 3{,}2\, kN$

Table. Glulam beam without protective layer according to 2020 version of Eurocode 5 after 30 minutes of fire

Cross-section / mm x mm	80x200	200x400	200x600	200x1000
Protective layer	none	none	none	none
Result / kNm	**3.2**	**91.5**	**216.5**	**625.2**
Required time / min	30	30	30	30
Strength class	GL24c	GL24c	GL24c	GL24c
b / mm	80	200	200	200
h / mm	200	400	600	1000
$\gamma_{M,fi}$	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	24	24	24
k_Θ	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	27.6	27.6	27.6
β_0 / mm/min	0.65	0.65	0.65	0.65
k_n	1.08	1.08	1.08	1.08
β_n / mm/min	0.702	0.702	0.702	0.702
$d_{char,n}$ / mm	21.06	21.06	21.06	21.06
d_0 / mm	7	7	7	7
d_{ef} / mm	28.06	28.06	28.06	28.06
b_{fi} / mm	23.88	143.88	143.88	143.88
h_{fi} / mm	171.94	371.94	571.94	971.94
W_{fi} / mm^3	117662.2	3317377.9	7844226.4	22653123.4
$M_{max,fi}$ / kNm	3.2	91.5	216.5	625.2

Table. Glulam beam without protective layer according to 2020 version of Eurocode 5 after 60 minutes of fire

Cross-section / mm x mm	80x200	200x400	200x600	200x1000
Protective layer	none	none	none	none
Result / kNm	**0**	**53.3**	**132.2**	**395.7**
Required time / min	60	60	60	60
Strength class	GL24c	GL24c	GL24c	GL24c
b / mm	80	200	200	200
h / mm	200	400	600	1000
$\gamma_{M,fi}$	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	24	24	24
k_{Θ}	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	27.6	27.6	27.6
β_0 / mm/min	0.65	0.65	0.65	0.65
k_n	1.08	1.08	1.08	1.08
β_n / mm/min	0.702	0.702	0.702	0.702
$d_{char,n}$ / mm	42.12	42.12	42.12	42.12
d_0 / mm	10	10	10	10
d_{ef} / mm	52.12	52.12	52.12	52.12
b_{fi} / mm	0	95.76	95.76	95.76
h_{fi} / mm	147.88	347.88	547.88	947.88
W_{fi} / mm^3	0	1931487.1	4790753	14339684.9
$M_{max,fi}$ / kNm	0	53.3	132.2	395.7

Table. Glulam beam without protective layer according to 2020 version of Eurocode 5 after 90 minutes of fire

Cross-section / mm x mm	80x200	200x400	200x600	200x1000
Protective layer	none	none	none	none
Result / kNm	**0**	**26.3**	**68.4**	**211.9**
Required time / min	90	90	90	90
Strength class	GL24c	GL24c	GL24c	GL24c
b / mm	80	200	200	200
h / mm	200	400	600	1000
$\gamma_{M,fi}$	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	24	24	24
k_{Θ}	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	27.6	27.6	27.6
β_0 / mm/min	0.65	0.65	0.65	0.65
k_n	1.08	1.08	1.08	1.08
β_n / mm/min	0.702	0.702	0.702	0.702
$d_{char,n}$ / mm	63.18	63.18	63.18	63.18
d_0 / mm	10	10	10	10
d_{ef} / mm	73.18	73.18	73.18	73.18
b_{fi} / mm	0	53.64	53.64	53.64
h_{fi} / mm	126.82	326.82	526.82	926.82
W_{fi} / mm^3	0	954893.1	2481201.5	7679418.1
$M_{max,fi}$ / kNm	0	26.3	68.4	211.9

Appendix 10 Calculations of glulam beam with one layer of GtA 12,5 according to 2020 version of Eurocode 5

height	h = 200 mm
width	b = 80 mm
material	GL24c
design strength in fire	$f_{d,fi} = 27{,}6 \frac{N}{mm^2}$
time	30 min
sides open to fire	3
protection	GtA 12,5
fire protective panel thickness	h_p = 15 mm

Reduced cross-section method

$k_{gd} = \begin{cases} 1{,}0 \\ 2{,}0 \end{cases}$ $\quad k_{gd} = 1{,}0$

$k_n = \begin{cases} 1{,}23 \\ 1{,}08 \end{cases}$ $\quad k_n = 1{,}08$

$k_g = \begin{cases} 1{,}0 \\ 2{,}0 \end{cases}$ $\quad k_g = 1{,}0$

$k_2 = 1 - 0{,}018 h_p$ $\quad k_2 = 1 - 0{,}018 * 12{,}5 = 0{,}775$

$k_3 = 2{,}0$

$k_4 = 1{,}0$

$\beta_{n,phase2} = \prod_{k_i} k_i \, \beta_0 = k_{gd} k_n k_2 \beta_0$ $\quad \beta_{n,phase2} = 1{,}0 * 1{,}08 * 0{,}775 * 0{,}65 = 0{,}54$

$\beta_{n,phase3} = \prod_{k_i} k_i \, \beta_0 = k_{gd} k_n k_3 \beta_0$ $\quad \beta_{n,phase3} = 1{,}0 * 1{,}08 * 2{,}0 * 0{,}65 = 1{,}40$

$\beta_{n,phase4} = \prod_{k_i} k_i \, \beta_0 = k_{gd} k_n k_4 \beta_0$ $\quad \beta_{n,phase4} = 1{,}0 * 1{,}08 * 1{,}0 * 065 = 0{,}70$

$t_{f,pr} = t_{ch} = \sum t_{prot}$

$\sum t_{prot} = 30 \left(\frac{h_p}{15}\right)^{1,2}$ $\quad \sum t_{prot} = 30 \left(\frac{12{,}5}{15}\right)^{1,2} = 24{,}1 \, min$

$t_a = = min \begin{cases} 2 \, t_{f,pr} \\ t_{f,pr} + \frac{25 - (t_f - t_{ch}) \beta_{n,phase}}{\beta_{n,phase3}} \end{cases}$ $\quad t_a = min \begin{cases} 2 * 24{,}1 = 48{,}2 \, min \\ 24{,}1 + \frac{25 - (24{,}1 - 24{,}1) * 0{,}54}{1{,}40} = 41{,}9 \, min \end{cases} = 41{,}9 \, min$

$d_{char,n,t_f} = (t_f - t_{ch}) \beta_{n,phase2}$ $\quad d_{char,n,t_f} = (24{,}1 - 24{,}1) * 0{,}54 = 0 \, mm$

$$d_{char,n,t} = d_{char,n,t_f} + (t - t_f)\beta_{n,phase3}$$ $$d_{char,n,t} = 0 + (30 - 24{,}1) * 1{,}4 = 8{,}28\ mm$$

$$d_{ef} = d_{char,n} + d_0$$ $$d_{ef} = 8{,}28 + 7 = 15{,}28\ mm$$

$$b_{ef} = b - k_{sides} d_{ef}$$ $$b_{ef} = 80 - 2 * 15{,}28 = 49{,}45\ mm$$

$$h_{ef} = h - k_{sides} d_{ef}$$ $$h_{ef} = 200 - 1 * 15{,}28 = 184{,}72mm$$

$$W_{ef} = \frac{b_{ef} {h_{ef}}^2}{6}$$ $$W_{ef} = \frac{49{,}45 * 184{,}72^2}{6} = 281207\ mm^3$$

$$M_{max,fi} = W_{ef} f_{d,fi} 10^{-6}$$ $$M_{max,fi} = 281207 * 27{,}6 * 10^{-6} = 7{,}7\ kN$$

Table. Glulam beam with one layer of GtA 12,5 according to 2020 version of Eurocode 5 after 30 minutes of fire

Cross-section / mm x mm	80x200	200x400	200x600	200x1000
Protective layer	GtA12,5	GtA12,5	GtA12,5	GtA12,5
Result / kNm	**7.7**	**115.3**	**266.4**	**755.8**
Required time / min	30	30	30	30
Strength class	GL24c	GL24c	GL24c	GL24c
b / mm	80	200	200	200
h / mm	200	400	600	1000
$\gamma_{M,fi}$	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	24	24	24
k_Θ	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	27.6	27.6	27.6
β_0 / mm/min	0.65	0.65	0.65	0.65
h_p / mm	12.5	12.5	12.5	12.5
k_2	0.775	0.775	0.775	0.775
k_3	2	2	2	2
k_4	1	1	1	1
k_n	1.08	1.08	1.08	1.08
$k_n\beta_0$ / mm/min	0.70	0.70	0.70	0.70
$k_2k_n\beta_0$ / mm/min	0.54	0.54	0.54	0.54
$k_3k_n\beta_0$ / mm/min	1.40	1.40	1.40	1.40
$k_4k_n\beta_0$ mm/min	0.702	0.702	0.702	0.702
$t_{f,degr}$ / min	-	-	-	-
$t_{prot,i}$ / min	24.10481	24.10481	24.10481	24.10481
t_{ch} / min	24.10481	24.10481	24.10481	24.10481
t_f / min	24.10481	24.10481	24.10481	24.10481
t_a / min	41.91	41.91	41.91	41.91
$d_{char,n\ tf}$ / mm	0.00	0.00	0.00	0.00
$d_{char,n\ ta}$ / mm	25.00	25.00	25.00	25.00
$d_{char,n\ t}$ / mm	8.28	8.28	8.28	8.28
d_0 / mm	7.00	7.00	7.00	7.00
d_{ef} / mm	15.28	15.28	15.28	15.28
b_{fi} / mm	49.45	169.45	169.45	169.45
h_{fi} / mm	184.72	384.72	584.72	984.72
W_{fi} / mm^3	281206.5	4180012	9655649	27384775
$M_{max,fi}$ / kNm	7.7	115.3	266.4	755.8

Table. Glulam beam with one layer of GtA 12,5 according to 2020 version of Eurocode 5 after 60 minutes of fire

Cross-section / mm x mm	80x200	200x400	200x600	200x1000
Protective layer	GtA12,5	GtA12,5	GtA12,5	GtA12,5
Result / kNm	**0**	**59.7**	**146.7**	**436.3**
Required time / min	60	60	60	60
Strength class	GL24c	GL24c	GL24c	GL24c
b / mm	80	200	200	200
h / mm	200	400	600	1000
$\gamma_{M,fi}$	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	24	24	24
k_{Θ}	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	27.6	27.6	27.6
β_0 / mm/min	0.65	0.65	0.65	0.65
h_p / mm	12.5	12.5	12.5	12.5
k_2	0.775	0.775	0.775	0.775
k_3	2	2	2	2
k_4	1	1	1	1
k_n	1.08	1.08	1.08	1.08
$k_n\beta_0$ / mm/min	0.70	0.70	0.70	0.70
$k_2k_n\beta_0$ / mm/min	0.54	0.54	0.54	0.54
$k_3k_n\beta_0$ / mm/min	1.40	1.40	1.40	1.40
$k_4k_n\beta_0$ mm/min	0.702	0.702	0.702	0.702
$t_{f,degr}$ / min	-	-	-	-
$t_{prot,i}$ / min	24.10481	24.10481	24.10481	24.10481
t_{ch} / min	24.10481	24.10481	24.10481	24.10481
t_f / min	24.10481	24.10481	24.10481	24.10481
t_a / min	41.91	41.91	41.91	41.91
$d_{char,n\ tf}$ / mm	0.00	0.00	0.00	0.00
$d_{char,n\ ta}$ / mm	25.00	25.00	25.00	25.00
$d_{char,n\ t}$ / mm	37.70	37.70	37.70	37.70
d_0 / mm	10.00	10.00	10.00	10.00
d_{ef} / mm	47.70	47.70	47.70	47.70
b_{fi} / mm	0.00	104.60	104.60	104.60
h_{fi} / mm	152.30	352.30	552.30	952.30
W_{fi} / mm^3	0	2163828	5317973	15810389
$M_{max,fi}$ / kNm	0	59.7	146.7	436.3

Table. Glulam beam with one layer of GtA 12,5 according to 2020 version of Eurocode 5 after 90 minutes of fire

Cross-section / mm x mm	80x200	200x400	200x600	200x1000
Protective layer	GtA12,5	GtA12,5	GtA12,5	GtA12,5
Result / kNm	**0**	**31.5**	**81.1**	**249.2**
Required time / min	90	90	90	90
Strength class	GL24c	GL24c	GL24c	GL24c
b / mm	80	200	200	200
h / mm	200	400	600	1000
$\gamma_{M,fi}$	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	24	24	24
k_Θ	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	27.6	27.6	27.6
β_0 / mm/min	0.65	0.65	0.65	0.65
h_p / mm	12.5	12.5	12.5	12.5
k_2	0.775	0.775	0.775	0.775
k_3	2	2	2	2
k_4	1	1	1	1
k_n	1.08	1.08	1.08	1.08
$k_n\beta_0$ / mm/min	0.70	0.70	0.70	0.70
$k_2k_n\beta_0$ / mm/min	0.54	0.54	0.54	0.54
$k_3k_n\beta_0$ / mm/min	1.40	1.40	1.40	1.40
$k_4k_n\beta_0$ mm/min	0.702	0.702	0.702	0.702
$t_{f,degr}$ / min	-	-	-	-
$t_{prot,i}$ / min	24.10481	24.10481	24.10481	24.10481
t_{ch} / min	24.10481	24.10481	24.10481	24.10481
t_f / min	24.10481	24.10481	24.10481	24.10481
t_a / min	41.91	41.91	41.91	41.91
$d_{char,n\ tf}$ / mm	0.00	0.00	0.00	0.00
$d_{char,n\ ta}$ / mm	25.00	25.00	25.00	25.00
$d_{char,n\ t}$ / mm	58.76	58.76	58.76	58.76
d_0 / mm	10.00	10.00	10.00	10.00
d_{ef} / mm	68.76	68.76	68.76	68.76
b_{fi} / mm	0.00	62.48	62.48	62.48
h_{fi} / mm	131.24	331.24	531.24	931.24
W_{fi} / mm^3	0	1142619	2938975	9031012
$M_{max,fi}$ / kNm	0	31.5	81.1	249.2

Appendix 11 Calculations of glulam beam with one layer of GtF 15 according to 2020 version of Eurocode 5

height	h = 200 mm
width	b = 80 mm
material	GL24c
design strength in fire	$f_{d,fi} = 27{,}6\frac{N}{mm^2}$
time	30 min
sides open to fire	3
protection	GtF 15
fire protective panel thickness	h_p = 15 mm

Reduced cross-section method

$k_{gd} = \begin{cases}1{,}0\\2{,}0\end{cases}$ $\quad k_{gd} = 1{,}0$

$k_n = \begin{cases}1{,}23\\1{,}08\end{cases}$ $\quad k_n = 1{,}08$

$k_2 = 1 - 0{,}018h_p$ $\quad k_2 = 1 - 0{,}018 * 15 = 0{,}73$

$k_3 = 2{,}0$

$k_4 = 1{,}0$

$\beta_{n,phase2} = \prod_{k_i} k_i\,\beta_0 = k_{gd}k_nk_2\beta_0$ $\quad \beta_{n,phase2} = 1{,}0 * 1{,}08 * 0{,}73 * 0{,}65 = 0{,}51$

$\beta_{n,phase3} = \prod_{k_i} k_i\,\beta_0 = k_{gd}k_nk_3\beta_0$ $\quad \beta_{n,phase3} = 1{,}0 * 1{,}08 * 2{,}0 * 0{,}65 = 1{,}40$

$\beta_{n,phase4} = \prod_{k_i} k_i\,\beta_0 = k_{gd}k_nk_4\beta_0$ $\quad \beta_{n,phase4} = 1{,}0 * 1{,}08 * 1{,}0 * 065 = 0{,}70$

$t_{f,pr} = 1{,}2\ (1{,}6h_p + 3)$ $\quad t_{f,pr} = 1{,}2(1{,}6 * 15 + 3) = 32{,}4\ min$

$t_{prot} = 30\left(\frac{h_p}{15}\right)^{1{,}2}$ $\quad t_{prot} = 30\left(\frac{15}{15}\right)^{1{,}2} = 30{,}0\ min$

$t_{ch} = min\begin{cases}\sum t_{prot}\\ t_{f,pr}\end{cases}$ $\quad t_{ch} = min\begin{cases}30{,}0\ min\\32{,}4\ min\end{cases} = 30{,}0\ min$

$t_a = min\begin{cases}2\ t_{f,pr}\\ t_{f,pr} + \frac{25 - (t_f - t_{ch})\beta_{n,phase2}}{\beta_{n,phase3}}\end{cases}$ $\quad t_a = min\begin{cases}2 * 32{,}4 = 54\ min\\ 32{,}4 + \frac{25 - (32{,}4 - 30) * 0{,}51}{1{,}40} = 49{,}33\ min\end{cases} = 49{,}33\ min$

$d_{char,n,t} = (t - t_{ch})\beta_{n,phase2}$ $\quad d_{char,n,t} = (30 - 30) * 0{,}51 = 0\ mm$

$d_{ef} = d_{char,n} + d_0$ $\quad d_{ef} = 0 + 7 = 7\ mm$

$b_{ef} = b - k_{sides} d_{ef}$ $\quad$ $b_{ef} = 80 - 2 * 7 = 66\ mm$

$h_{ef} = h - k_{sides} d_{ef}$ $\quad$ $h_{ef} = 200 - 1 * 7 = 193\ mm$

$W_{ef} = \frac{b_{ef} {h_{ef}}^2}{6}$ $\quad$ $W_{ef} = \frac{66 * 193^2}{6} = 409739\ mm^3$

$M_{max,fi} = W_{ef} f_{d,fi} 10^{-6}$ $\quad$ $M_{max,fi} = 409739 * 27{,}6 * 10^{-6} = 11{,}3\ kN$

Table. Glulam beam with one layer of GtF 15 according to 2020 version of Eurocode 5 after 30 minutes of fire

Cross-section / mm x mm	80x200	200x400	200x600	200x1000
Protective layer	GtF15	GtF15	GtF15	GtF15
Result / kNm	**11.3**	**132.1**	**300.8**	**843.6**
Required time / min	30	30	30	30
Strength class	GL24c	GL24c	GL24c	GL24c
b / mm	80	200	200	200
h / mm	200	400	600	1000
$\gamma_{M,fi}$	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	24	24	24
k_Θ	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	27.6	27.6	27.6
β_0 / mm/min	0.65	0.65	0.65	0.65
h_p / mm	15	15	15	15
k_2	0.73	0.73	0.73	0.73
k_3	2	2	2	2
k_4	1	1	1	1
k_n	1.08	1.08	1.08	1.08
$k_n\beta_0$ / mm/min	0.70	0.70	0.70	0.70
$k_2k_n\beta_0$ / mm/min	0.51	0.51	0.51	0.51
$k_3k_n\beta_0$ / mm/min	1.40	1.40	1.40	1.40
$k_4k_n\beta_0$ mm/min	0.702	0.702	0.702	0.702
$t_{f,degr}$ / min	32.4	32.4	32.4	32.4
$t_{prot,i}$ / min	30	30	30	30
t_{ch} / min	30	30	30	30
t_f / min	32.4	32.4	32.4	32.4
t_a / min	49.33	49.33	49.33	49.33
$d_{char,n\ tf}$ / mm	1.23	1.23	1.23	1.23
$d_{char,n\ ta}$ / mm	25.00	25.00	25.00	25.00
$d_{char,n\ t}$ / mm	0.00	0.00	0.00	0.00
d_0 / mm	7.00	7.00	7.00	7.00
d_{ef} / mm	7.00	7.00	7.00	7.00
b_{fi} / mm	66.00	186.00	186.00	186.00
h_{fi} / mm	193.00	393.00	593.00	993.00
W_{fi} / mm^3	409739	4787919	10901119	30567519
$M_{max,fi}$ / kNm	11.3	132.1	300.8	843.6

Table. Glulam beam with one layer of GtF 15 according to 2020 version of Eurocode 5 after 60 minutes of fire

Cross-section / mm x mm	80x200	200x400	200x600	200x1000
Protective layer	GtF15	GtF15	GtF15	GtF15
Result / kNm	**0**	**67.6**	**164.4**	**485**
Required time / min	60	60	60	60
Strength class	GL24c	GL24c	GL24c	GL24c
b / mm	80	200	200	200
h / mm	200	400	600	1000
$\gamma_{M,fi}$	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	24	24	24
k_Θ	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	27.6	27.6	27.6
β_0 / mm/min	0.65	0.65	0.65	0.65
h_p / mm	15	15	15	15
k_2	0.73	0.73	0.73	0.73
k_3	2	2	2	2
k_4	1	1	1	1
k_n	1.08	1.08	1.08	1.08
$k_n\beta_0$ / mm/min	0.70	0.70	0.70	0.70
$k_2k_n\beta_0$ / mm/min	0.51	0.51	0.51	0.51
$k_3k_n\beta_0$ / mm/min	1.40	1.40	1.40	1.40
$k_4k_n\beta_0$ mm/min	0.702	0.702	0.702	0.702
$t_{f,degr}$ / min	32.4	32.4	32.4	32.4
$t_{prot,i}$ / min	30	30	30	30
t_{ch} / min	30	30	30	30
t_f / min	32.4	32.4	32.4	32.4
t_a / min	49.33	49.33	49.33	49.33
$d_{char,n\ tf}$ / mm	1.23	1.23	1.23	1.23
$d_{char,n\ ta}$ / mm	25.00	25.00	25.00	25.00
$d_{char,n\ t}$ / mm	32.49	32.49	32.49	32.49
d_0 / mm	10.00	10.00	10.00	10.00
d_{ef} / mm	42.49	42.49	42.49	42.49
b_{fi} / mm	0.00	115.02	115.02	115.02
h_{fi} / mm	157.51	357.51	557.51	957.51
W_{fi} / mm^3	0	2450174	5958351	17575491
$M_{max,fi}$ / kNm	0	67.6	164.4	485

Table. Glulam beam with one layer of GtF 15 according to 2020 version of Eurocode 5 after 90 minutes of fire

Cross-section / mm x mm	80x200	200x400	200x600	200x1000
Protective layer	GtF15	GtF15	GtF15	GtF15
Result / kNm	**0**	**37.9**	**96.5**	**294**
Required time / min	90	90	90	90
Strength class	GL24c	GL24c	GL24c	GL24c
b / mm	80	200	200	200
h / mm	200	400	600	1000
$\gamma_{M,fi}$	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	24	24	24
k_Θ	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	27.6	27.6	27.6
β_0 / mm/min	0.65	0.65	0.65	0.65
h_p / mm	15	15	15	15
k_2	0.73	0.73	0.73	0.73
k_3	2	2	2	2
k_4	1	1	1	1
k_n	1.08	1.08	1.08	1.08
$k_n\beta_0$ / mm/min	0.70	0.70	0.70	0.70
$k_2k_n\beta_0$ / mm/min	0.51	0.51	0.51	0.51
$k_3k_n\beta_0$ / mm/min	1.40	1.40	1.40	1.40
$k_4k_n\beta_0$ mm/min	0.702	0.702	0.702	0.702
$t_{f,degr}$ / min	32.4	32.4	32.4	32.4
$t_{prot,i}$ / min	30	30	30	30
t_{ch} / min	30	30	30	30
t_f / min	32.4	32.4	32.4	32.4
t_a / min	49.33	49.33	49.33	49.33
$d_{char,n\ tf}$ / mm	1.23	1.23	1.23	1.23
$d_{char,n\ ta}$ / mm	25.00	25.00	25.00	25.00
$d_{char,n\ t}$ / mm	53.55	53.55	53.55	53.55
d_0 / mm	10.00	10.00	10.00	10.00
d_{ef} / mm	63.55	63.55	63.55	63.55
b_{fi} / mm	0.00	72.90	72.90	72.90
h_{fi} / mm	136.45	336.45	536.45	936.45
W_{fi} / mm^3	0	1375356	3496494	10654756
$M_{max,fi}$ / kNm	0	37.9	96.5	294

Appendix 12 Calculations of unprotected glulam column according to 2020 version of Eurocode 5

column height	l=3m=3000mm
height	h = 80 mm
width	b = 80 mm
material	GL24h
design strength in fire	$f_{d,fi} = 24{,}7\frac{N}{mm^2}$
design compressive strengths along the grain	$f_{c,o,g,k} = 21{,}5\frac{N}{mm^2}$
the fifth percentile value of the modulus of elasticity	$E_{0,g,05} = 9600$
time	30 min
sides open to fire	4
protection	none

Reduced cross-section method

$k_{gd} = \begin{cases}1{,}0\\2{,}0\end{cases}$ $\quad$ $k_{gd} = 1{,}0$

$k_n = \begin{cases}1{,}23\\1{,}08\end{cases}$ $\quad$ $k_n = 1{,}08$

$\beta_n = \prod_{k_i} k_i \beta_0$ $\quad$ $\beta_n = 1{,}0 * 1{,}08 * 0{,}65 = 0{,}70\, mm/min$

$d_{char,n} = \beta_n t$ $\quad$ $d_{char,n} = 0{,}70 * 30 = 21{,}0\, mm$

$d_{ef} = d_{char,n} + d_0$ $\quad$ $d_{ef} = 21 + 14 = 35\, mm$

$b_{ef} = b - k_{sides} d_{ef}$ $\quad$ $b_{ef} = 80 - 2 * 35 = 10\, mm$

$h_{ef} = h - k_{sides} d_{ef}$ $\quad$ $h_{ef} = 80 - 2 * 35 = 0\, mm$

$A_{ef} = b_{ef} h_{ef}$ $\quad$ $A_{ef} = 10 * 10 = 100\, mm^2$

$N_{max,fi} = A_{ef} f_{d,fi} 10^{-3}$ $\quad$ $N_{max,fi} = 100 * 24{,}7 * 10^{-3} = 2{,}4\, kN$

Slenderness

$I = \frac{b_{ef} {h_{ef}}^3}{12}$ $\quad$ $I = \frac{10 * 10^3}{12} = 794\, mm^4$

$i = \sqrt{\frac{I}{A_{fi}}}$ $\quad$ $i = \sqrt{\frac{794}{100}} = 2{,}9\, mm$

$l_0 = \mu l$ $\quad$ $l_0 = 0{,}7 * 3000 = 2100\, mm$

$\lambda_y = \frac{l_0}{i}$ $\quad$ $\lambda_y = \frac{2100}{2{,}9} = 736{,}2$

$$\lambda_{rel,y} = \frac{\lambda_y}{\pi}\sqrt{\frac{f_{c,o,g,k}}{E_{0,g,05}}} \qquad \lambda_{rel,y} = \frac{736{,}2}{\pi}\sqrt{\frac{21{,}5}{9600}} = 11{,}1$$

$$\beta_c = 0{,}1$$

$$k_y = 0{,}5\left(1 + \beta_c\left(\lambda_{rel,y} - 0{,}3\right) + {\lambda_{rel,y}}^2\right) \qquad k_y = 0{,}5\;(1 + 0{,}1(11{,}1 - 0{,}3) + 11{,}1^2) = 62{,}5$$

$$k_{cy} = \frac{1}{k_y + \sqrt{{k_y}^2 - {\lambda_{rel,y}}^2}} \qquad k_{cy} = \frac{1}{62{,}5 + \sqrt{62{,}5^2 - 11{,}1^2}} = 0{,}01$$

$$\sigma_{c,0,d} = k_{cy} f_{c,o,g,k} \qquad \sigma_{c,0,d} = 0{,}01 * 21{,}5 = 0{,}17\,\frac{N}{mm^2}$$

$$N_{max,fi} = A_{fi}\sigma_{c,0,d}10^{-3} \qquad N_{max,fi} = 100 * 0{,}17 * 10^{-3} = 0{,}01\;kN$$

Table. Glulam column with no protective layer according to 2020 version of Eurocode after 30 minutes of fire

Cross-section / mm x mm	80x80	200x200	400x400
Protective layer	none	none	none
Result / kNm	**0**	**317**	**2331.2**
Required time / min	30	30	30
Strength class	GL24h	GL24c	GL24c
L / m	3	3	3
b / mm	80	200	400
h / mm	80	200	400
$\gamma_{M,fi}$	1	1	1
k_{fi}	1.15	1.15	1.15
$f_{c,0,g,k}$ / kN/mm^2	21.5	21.5	21.5
$k_{mod,fi}$	1	1	1
$f_{d,fi}$ / kN/mm^2	24.725	24.725	24.725
β_0 / mm/min	0.65	0.65	0.65
k_n	1.08	1.08	1.08
β_n / mm/min	0.702	0.702	0.702
$d_{char,n}$ / mm	21.06	21.06	21.06
d_0 / mm	14	14	14
d_{ef} / mm	35.06	35.06	35.06
b_{fi} / mm	9.88	129.88	329.88
h_{fi} / mm	9.88	129.88	329.88
A_{fi} / mm^2	97.6	16868.8	108820.8
$N_{max,fi}$ / kN	2.4	417	2690.5
I / mm4	794.0476	23713075	9.87E+08
i / mm	2.852321	37.49314	95.22816
l0 / mm	2100	2100	2100
λy	736.2426	56.01024	22.0523
E0,05 / kN/mm2	9600	9601	9602
λrel,y	11.09059	0.843682	0.332156
ky	62.54013	0.883083	0.556772
kcy	0.008059	0.874184	0.9964
σc,0,d / kN/mm2	0.173263	18.79496	21.4226
Nmax,fi / kN	0.01691	317.0484	2331.225

Table. Glulam column with no protective layer according to 2020 version of Eurocode after 60 minutes of fire

Cross-section / mm x mm	80x80	200x200	400x400
Protective layer	none	none	none
Result / kNm	**0**	**78.4**	**1713.8**
Required time / min	60	60	60
Strength class	GL24h	GL24c	GL24c
L / m	3	3	3
b / mm	80	200	400
h / mm	80	200	400
$\gamma_{M,fi}$	1	1	1
k_{fi}	1.15	1.15	1.15
$f_{c,0,g,k}$ / kN/mm^2	21.5	21.5	21.5
$k_{mod,fi}$	1	1	1
$f_{d,fi}$ / kN/mm^2	24.725	24.725	24.725
β_0 / mm/min	0.65	0.65	0.65
k_n	1.08	1.08	1.08
β_n / mm/min	0.702	0.702	0.702
$d_{char,n}$ / mm	42.12	42.12	42.12
d_0 / mm	16	16	16
d_{ef} / mm	58.12	58.12	58.12
b_{fi} / mm	0	83.76	283.76
h_{fi} / mm	0	83.76	283.76
A_{fi} / mm^2	0	7015.7	80519.7
$N_{max,fi}$ / kN	0	173.4	1990.8
I / mm^4	0	4101715	5.4E+08
i / mm	0	24.17949	81.91448
l_0 / mm	2100	2100	2100
λ_y	0	86.85045	25.63649
$E_{0,05}$ / kN/mm^2	9600	9600	9600
$\lambda_{rel,y}$	0	1.308295	0.386182
k_y	0.485	1.406233	0.578878
k_{cy}	1.030928	0.520333	0.98999
$\sigma_{c,0,d}$ / kN/mm^2	21.5	11.18717	21.28479
$N_{max,fi}$ / kN	0	78.48582	1713.845

Table. Glulam column with no protective layer according to 2020 version of Eurocode after 90 minutes of fire

Cross-section / mm x mm	80x80	200x200	400x400
Protective layer	none	none	none
Result / kNm	**0**	**5.1**	**1231.7**
Required time / min	90	90	90
Strength class	GL24h	GL24c	GL24c
L / m	3	3	3
b / mm	80	200	400
h / mm	80	200	400
$\gamma_{M,fi}$	1	1	1
k_{fi}	1.15	1.15	1.15
$f_{c,0,g,k}$ / kN/mm^2	21.5	21.5	21.5
$k_{mod,fi}$	1	1	1
$f_{d,fi}$ / kN/mm^2	24.725	24.725	24.725
β_0 / mm/min	0.65	0.65	0.65
k_n	1.08	1.08	1.08
β_n / mm/min	0.702	0.702	0.702
$d_{char,n}$ / mm	63.18	63.18	63.18
d_0 / mm	16	16	16
d_{ef} / mm	79.18	79.18	79.18
b_{fi} / mm	0	41.64	241.64
h_{fi} / mm	0	41.64	241.64
A_{fi} / mm^2	0	1733.9	58389.9
$N_{max,fi}$ / kN	0	42.8	1443.6
I / mm^4	0	250531.1	2.84E+08
i / mm	0	12.0204	69.75545
l_0 / mm	2100	2100	2100
λ_y	0	174.7031	30.10517
$E_{0,05}$ / kN/mm^2	9600	9601	9602
$\lambda_{rel,y}$	0	2.63155	0.45345
k_y	0.485	4.079105	0.610481
k_{cy}	1.030928	0.138969	0.981139
$\sigma_{c,0,d}$ / kN/mm^2	21.5	2.987837	21.0945
$N_{max,fi}$ / kN	0	5.18061	1231.706

Appendix 13 Calculations of glulam column with one layer of GtA 12,5 according to 2020 version of Eurocode 5

column height	l=3m=3000mm
height	h = 80 mm
width	b = 80 mm
material	GL24h
design strength in fire	$f_{d,fi} = 24{,}7 \frac{N}{mm^2}$
design compressive strengths along the grain	$f_{c,o,g,k} = 21{,}5 \frac{N}{mm^2}$
the fifth percentile value of the modulus of elasticity	$E_{0,g,05} = 9600$
time	30 min
sides open to fire	4
protection	GtA 12,5

Reduced cross-section method

$k_{gd} = \begin{cases} 1{,}0 \\ 2{,}0 \end{cases}$ $\qquad k_{gd} = 1{,}0$

$k_n = \begin{cases} 1{,}23 \\ 1{,}08 \end{cases}$ $\qquad k_n = 1{,}08$

$k_2 = 1 - 0{,}018 h_p$ $\qquad k_2 = 1 - 0{,}018 * 12{,}5 = 0{,}775$

$k_3 = 2{,}0$

$k_4 = 1{,}0$

$\beta_{n,phase2} = \prod_{k_i} k_i \beta_0 = k_{gd} k_n k_g k_2 \beta_0$ $\qquad \beta_{n,phase2} = 1{,}0 * 1{,}08 * 1{,}0 * 0{,}775 * 0{,}65 = 0{,}54$

$\beta_{n,phase3} = \prod_{k_i} k_i \beta_0 = k_{gd} k_n k_g k_3 \beta_0$ $\qquad \beta_{n,phase3} = 1{,}0 * 1{,}08 * 1{,}0 * 2{,}0 * 0{,}65 = 1{,}40$

$\beta_{n,phase4} = \prod_{k_i} k_i \beta_0 = k_{gd} k_n k_4 \beta_0$ $\qquad \beta_{n,phase4} = 1{,}0 * 1{,}08 * 1{,}0 * 065 = 0{,}70$

$t_{f,pr} = 1{,}2(1{,}8 h_p - 4{,}8)$ $\qquad t_{f,pr} = 1{,}2 * (1{,}8 * 12{,}5 - 4{,}8) = 21\ min$

$t_{prot} = 30 \left(\frac{h_p}{15}\right)^{1,2}$ $\qquad t_{prot} = 30 \left(\frac{12{,}5}{15}\right)^{1,2} = 24{,}1\ min$

$t_{ch} = min \begin{cases} \sum t_{prot} \\ t_{f,pr} \end{cases}$ $\qquad t_{ch} = min \begin{cases} 24{,}1\ min \\ 21\ min \end{cases} = 21\ min$

$$t_a = min\begin{cases} 2\ t_{f,pr} \\ t_{f,pr} + \dfrac{25-(t_f - t_{ch})\beta_{n,phas}}{\beta_{n,phase3}} \end{cases} \qquad t_a = min\begin{cases} 2*21 = 42 \\ 21 + \dfrac{25-(21-21)*0{,}54}{1{,}40} = 38{,}8 \end{cases} = 38{,}8 min$$

$$d_{char,n,t_f} = (t_f - t_{ch})\beta_{n,phase2} \qquad d_{char,n,t_f} = (21-21)*0{,}54 = 0\ mm$$

$$d_{char,n,t} = d_{char,n,t_f} + (t - t_f)\beta_{n,phase3} \qquad d_{char,n,t} = 0 + (30-21)*1{,}40 = 12{,}6\ mm$$

$$d_{ef} = d_{char,n} + d_0 \qquad d_{ef} = 12{,}6 + 14 = 26{,}6\ mm$$

$$b_{ef} = b - k_{sides}d_{ef} \qquad b_{ef} = 80 - 2*26{,}6 = 26{,}8\ mm$$

$$h_{ef} = h - k_{sides}d_{ef} \qquad h_{ef} = 80 - 2*26{,}6 = 26{,}8\ mm$$

$$A_{ef} = b_{ef}h_{ef} \qquad A_{ef} = 26{,}8*26{,}8 = 718{,}24\ mm^2$$

$$N_{max,fi} = A_{ef}f_{d,fi}10^{-3} \qquad N_{max,fi} = 718{,}24*24{,}7*10^{-3} = 7{,}5\ kN$$

Slenderness

$$I = \frac{b_{fi}{h_{fi}}^3}{12} \qquad I = \frac{26{,}8*26{,}8^3}{12} = 42519\ mm^4$$

$$i = \sqrt{\frac{I}{A_{fi}}} \qquad i = \sqrt{\frac{42519}{718{,}24}} = 7{,}7\ mm$$

$$l_0 = \mu l \qquad l_0 = 0{,}7*3000 = 2100\ mm$$

$$\lambda_y = \frac{l_0}{i} \qquad \lambda_y = \frac{2100}{7{,}7} = 272{,}2$$

$$\lambda_{rel,y} = \frac{\lambda_y}{\pi}\sqrt{\frac{f_{c,o,g,k}}{E_{0,g,05}}} \qquad \lambda_{rel,y} = \frac{272{,}2}{\pi}\sqrt{\frac{21{,}5}{9600}} = 4{,}10$$

$$\beta_c = 0{,}1$$

$$k_y = 0{,}5\left(1 + \beta_c(\lambda_{rel,y} - 0{,}3) + {\lambda_{rel,y}}^2\right) \qquad k_y = 0{,}5\ (1 + 0{,}1(4{,}10 - 0{,}3) + 4{,}10^2) = 9{,}09$$

$$k_{cy} = \frac{1}{k_y + \sqrt{{k_y}^2 - {\lambda_{rel,y}}^2}} \qquad k_{cy} = \frac{1}{9{,}09 + \sqrt{9{,}09^2 - 4{,}10^2}} = 0{,}06$$

$$\sigma_{c,0,d} = k_{cy}f_{c,o,g,k} \qquad \sigma_{c,0,d} = 0{,}06*21{,}5 = 1{,}25\frac{N}{mm^2}$$

$$N_{max,fi} = A_{fi}\sigma_{c,0,d}10^{-3} \qquad N_{max,fi} = 718{,}24*1{,}25*10^{-3} = 0{,}9\ kN$$

Table. Glulam column with one layer of GtA 12,5 according to 2020 version of Eurocode after 30 minutes of fire

Cross-section / mm x mm	80x80	200x200	400x400
Protective layer	GtA12,5	GtA12,5	GtA12,5
Result / kNm	**0.8**	**424.1**	**2580.1**
Required time / min	30	30	30
Strength class	GL24h	GL24c	GL24c
L / m	3	3	3
b / mm	80	200	400
h / mm	80	200	400
$\gamma_{M,fi}$	1	1	1
k_{fi}	1.15	1.15	1.15
$f_{c,0,g,k}$ / kN/mm^2	21.5	21.5	21.5
$k_{mod,fi}$	1	1	1
$f_{d,fi}$ / kN/mm^2	24.725	24.725	24.725
β_0 / mm/min	0.65	0.65	0.65
h_p / mm	12.5	12.5	12.5
k_2	0.775	0.775	0.775
k_3	2	2	2
k_4	1	1	1
k_n	1.08	1.08	1.08
$k_n\beta_0$ / mm/min	0.70	0.70	0.70
$k_2k_n\beta_0$ / mm/min	0.54	0.54	0.54
$k_3k_n\beta_0$ / mm/min	1.40	1.40	1.40
$k_4k_n\beta_0$ mm/min	0.702	0.702	0.702
$t_{f,degr}$ / min	21	21	21
$t_{prot,i}$ / min	24.10481	24.10481	24.10481
t_{ch} / min	21	21	21
t_f / min	21	21	21
t_a / min	38.81	38.81	38.81
$d_{char,n\ tf}$ / mm	0.00	0.00	0.00
$d_{char,n\ ta}$ / mm	25.00	25.00	25.00
$d_{char,n\ t}$ / mm	12.64	12.64	12.64
d_0 / mm	14.00	14.00	14.00
d_{ef} / mm	26.64	26.64	26.64
b_{fi} / mm	26.73	146.73	346.73
h_{fi} / mm	26.73	146.73	346.73
A_{fi} / mm^2	714.386	21529.11	120220.3
$N_{max,fi}$ / kN	17.6	532.3	2972.4

Table continues

I / mm^4	42528.94	38625200	1.2E+09
i / mm	7.715709	42.35673	100.0918
l_0 / mm	2100	2100	2100
λ_y	272.172	49.5789	20.98075
$E_{0,05}$ / kN/mm^2	9600	9600	9600
$\lambda_{rel,y}$	4.099937	0.746845	0.316049
k_y	9.094739	0.801231	0.550746
k_{cy}	0.058096	0.916261	0.99822
$\sigma_{c,0,d}$ / kN/mm^2	1.249062	19.6996	21.46174
$N_{max,fi}$ / kN	0.892312	424.1149	2580.137

Table. Glulam column with one layer of GtA 12,5 according to 2020 version of Eurocode after 60 minutes of fire

Cross-section / mm x mm	80x80	200x200	400x400
Protective layer	GtA12,5	GtA12,5	GtA12,5
Result / kNm	**0**	**95.1**	**1769.7**
Required time / min	60	60	60
Strength class	GL24h	GL24c	GL24c
L / m	3	3	3
b / mm	80	200	400
h / mm	80	200	400
$\gamma_{M,fi}$	1	1	1
k_{fi}	1.15	1.15	1.15
$f_{c,0,g,k}$ / kN/mm^2	21.5	21.5	21.5
$k_{mod,fi}$	1	1	1
$f_{d,fi}$ / kN/mm^2	24.725	24.725	24.725
β_0 / mm/min	0.65	0.65	0.65
h_p / mm	12.5	12.5	12.5
k_2	0.775	0.775	0.775
k_3	2	2	2
k_4	1	1	1
k_n	1.08	1.08	1.08
$k_n\beta_0$ / mm/min	0.70	0.70	0.70
$k_2k_n\beta_0$ / mm/min	0.54	0.54	0.54
$k_3k_n\beta_0$ / mm/min	1.40	1.40	1.40
$k_4k_n\beta_0$ mm/min	0.702	0.702	0.702
$t_{f,degr}$ / min	21	21	21
$t_{prot,i}$ / min	24.10481	24.10481	24.10481
t_{ch} / min	21	21	21
t_f / min	21	21	21
t_a / min	38.81	38.81	38.81

Table continues

$d_{char,n\ tf}$ / mm	0.00	0.00	0.00
$d_{char,n\ ta}$ / mm	25.00	25.00	25.00
$d_{char,n\ t}$ / mm	39.88	39.88	39.88
d_0 / mm	16.00	16.00	16.00
d_{ef} / mm	55.88	55.88	55.88
b_{fi} / mm	0.00	88.24	288.24
h_{fi} / mm	0.00	88.24	288.24
A_{fi} / mm^2	0	7787.004	83084.6
$N_{max,fi}$ / kN	0	192.5	2054.2
I / mm^4	0	5053119	5.75E+08
i / mm	0	25.47385	83.20888
l_0 / mm	2100	2100	2100
λ_y	0	82.43748	25.23769
$E_{0,05}$ / kN/mm^2	9600	9600	9600
$\lambda_{rel,y}$	0	1.241819	0.380175
k_y	0.485	1.318149	0.576275
k_{cy}	1.030928	0.56812	0.990729
$\sigma_{c,0,d}$ / kN/mm^2	21.5	12.21459	21.30068
$N_{max,fi}$ / kN	0	95.11505	1769.759

Table. Glulam column with one layer of GtA 12,5 according to 2020 version of Eurocode after 90 minutes of fire

Cross-section / mm x mm	80x80	200x200	400x400
Protective layer	GtA12,5	GtA12,5	GtA12,5
Result / kNm	**0**	**7.7**	**1279.3**
Required time / min	90	90	90
Strength class	GL24h	GL24c	GL24c
L / m	3	3	3
b / mm	80	200	400
h / mm	80	200	400
$\gamma_{M,fi}$	1	1	1
k_{fi}	1.15	1.15	1.15
$f_{c,0,g,k}$ / kN/mm^2	21.5	21.5	21.5
$k_{mod,fi}$	1	1	1
$f_{d,fi}$ / kN/mm^2	24.725	24.725	24.725
β_0 / mm/min	0.65	0.65	0.65
h_p / mm	12.5	12.5	12.5
k_2	0.775	0.775	0.775
k_3	2	2	2
k_4	1	1	1
k_n	1.08	1.08	1.08

Table continues

$k_n\beta_0$ / mm/min	0.70	0.70	0.70
$k_2k_n\beta_0$ / mm/min	0.54	0.54	0.54
$k_3k_n\beta_0$ / mm/min	1.40	1.40	1.40
$k_4k_n\beta_0$ mm/min	0.702	0.702	0.702
$t_{f,degr}$ / min	21	21	21
$t_{prot,i}$ / min	24.10481	24.10481	24.10481
t_{ch} / min	21	21	21
t_f / min	21	21	21
t_a / min	38.81	38.81	38.81
$d_{char,n\ tf}$ / mm	0.00	0.00	0.00
$d_{char,n\ ta}$ / mm	25.00	25.00	25.00
$d_{char,n\ t}$ / mm	60.94	60.94	60.94
d_0 / mm	16.00	16.00	16.00
d_{ef} / mm	76.94	76.94	76.94
b_{fi} / mm	0.00	46.12	246.12
h_{fi} / mm	0.00	46.12	246.12
A_{fi} / mm^2	0	2127.423	60577.02
$N_{max,fi}$ / kN	0	52.6	1497.7
I / mm^4	0	377160.9	3.06E+08
i / mm	0	13.31485	71.04988
l_0 / mm	2100	2100	2100
λ_y	0	157.7186	29.5567
$E_{0,05}$ / kN/mm^2	9600	9600	9600
$\lambda_{rel,y}$	0	2.375837	0.445235
k_y	0.485	3.426093	0.606379
k_{cy}	1.030928	0.169647	0.982284
$\sigma_{c,0,d}$ / kN/mm^2	21.5	3.647408	21.11911
$N_{max,fi}$ / kN	0	7.75958	1279.333

Appendix 14 Calculations of glulam column with one layer of GtF 15 according to 2020 version of Eurocode 5

column height	l=3m=3000mm
height	h = 80 mm
width	b = 80 mm
material	GL24h
design strength in fire	$f_{d,fi} = 24{,}7\frac{N}{mm^2}$
design compressive strengths along the grain	$\mathrm{f_{c,o,g,k}} = 21{,}5\frac{\mathrm{N}}{\mathrm{mm}^2}$
the fifth percentile value of the modulus of elasticity	$\mathrm{E_{0,g,05}} = 9600$
time	30 min
sides open to fire	4
Protection	GtF15

Reduced cross-section method

$k_{gd} = \begin{cases} 1{,}0 \\ 2{,}0 \end{cases}$ $\quad$ $k_{gd} = 1{,}0$

$k_n = \begin{cases} 1{,}23 \\ 1{,}08 \end{cases}$ $\quad$ $k_n = 1{,}08$

$k_2 = 1 - 0{,}018h_p$ $\quad$ $k_2 = 1 - 0{,}018 * 15 = 0{,}73$

$k_3 = 2{,}0$

$k_4 = 1{,}0$

$\beta_{n,phase2} = \prod_{k_i} k_i\,\beta_0 = k_{gd}k_nk_2\beta_0$ $\quad$ $\beta_{n,phase2} = 1{,}0 * 1{,}08 * 0{,}73 * 0{,}65 = 0{,}51$

$\beta_{n,phase3} = \prod_{k_i} k_i\,\beta_0 = k_{gd}k_nk_3\beta_0$ $\quad$ $\beta_{n,phase3} = 1{,}0 * 1{,}08 * 2{,}0 * 0{,}65 = 1{,}40$

$\beta_{n,phase4} = \prod_{k_i} k_i\,\beta_0 = k_{gd}k_nk_4\beta_0$ $\quad$ $\beta_{n,phase4} = 1{,}0 * 1{,}08 * 1{,}0 * 065 = 0{,}70$

$t_{f,pr} = 1{,}2(3{,}9h_p - 16)$ $\quad$ $t_{f,pr} = 1{,}2 * (3{,}9 * 15 - 16) = 51\,min$

$t_{prot} = 30\left(\frac{h_p}{15}\right)^{1{,}2}$ $\quad$ $t_{prot} = 30\left(\frac{15}{15}\right)^{1{,}2} = 30{,}0\,min$

$t_{ch} = min\begin{cases} \sum t_{prot} \\ t_{f,pr} \end{cases}$ $\quad$ $t_{ch} = min\begin{cases} 30{,}0\,min \\ 51\,min \end{cases} = 30\,min$

$$t_a = min \begin{cases} 2\ t_{f,pr} \\ t_{f,pr} + \dfrac{25 - (t_f - t_{ch})\beta_{n,phas}}{\beta_{n,phase3}} \end{cases}$$

$$t_a = min \begin{cases} 2 * 51 = 102\ min \\ 51 + \dfrac{25 - (51 - 30) * 0{,}51}{1{,}40} = 61{,}14\ min \end{cases} = 61{,}14\ min$$

$$d_{char,n,t_f} = (t_f - t_{ch})\beta_{n,phase2}$$ $$d_{char,n,t_f} = (51 - 30) * 0{,}51 = 10{,}7\ mm$$

$$d_{char,n,t_a} = d_{char,n,t_f} + (t_a - t_f)\ \beta_{n,phase3}$$ $$d_{char,n,t_a} = 10{,}7 + (61{,}14 - 51) * 1{,}40 = 24{,}9\ mm$$

$$d_{char,n,t} = (t - t_{ch})\beta_{n,phase2}$$ $$d_{char,n,t} = (30 - 30) * 0{,}51 = 0\ mm$$

$$d_{ef} = d_{char,n} + d_0$$ $$d_{ef} = 0 + 14 = 14\ mm$$

$$b_{ef} = b - k_{sides}d_{ef}$$ $$b_{ef} = 80 - 2 * 14 = 52\ mm$$

$$h_{ef} = h - k_{sides}d_{ef}$$ $$h_{ef} = 80 - 2 * 14 = 52\ mm$$

$$A_{ef} = b_{ef}h_{ef}$$ $$A_{ef} = 52 * 52 = 2704\ mm^2$$

$$N_{max,fi} = A_{ef}f_{d,fi}10^{-3}$$ $$N_{max,fi} = 2704 * 24{,}7 * 10^{-3} = 66{,}8\ kN$$

Slenderness

$$I = \frac{b_{fi}{h_{fi}}^3}{12}$$ $$I = \frac{52{,}0 * 52{,}0^3}{12} = 609301 mm^4$$

$$i = \sqrt{\frac{I}{A_{fi}}}$$ $$i = \sqrt{\frac{609301}{2704}} = 15{,}0\ mm$$

$$l_0 = \mu l$$ $$l_0 = 0{,}7 * 3000 = 2100\ mm$$

$$\lambda_y = \frac{l_0}{i}$$ $$\lambda_y = \frac{2100}{15{,}0} = 139{,}9$$

$$\lambda_{rel,y} = \frac{\lambda_y}{\pi}\sqrt{\frac{f_{c,o,g,k}}{E_{0,g,05}}}$$ $$\lambda_{rel,y} = \frac{139{,}9}{\pi}\sqrt{\frac{21{,}5}{9600}} = 2{,}11$$

$$\beta_c = 0{,}1$$

$$k_y = 0{,}5\left(1 + \beta_c\left(\lambda_{rel,y} - 0{,}3\right) + {\lambda_{rel,y}}^2\right)$$ $$k_y = 0{,}5\ (1 + 0{,}1(2{,}11 - 0{,}3) + 2{,}11^2) = 2{,}81$$

$$k_{cy} = \frac{1}{k_y + \sqrt{{k_y}^2 - {\lambda_{rel,y}}^2}}$$ $$k_{cy} = \frac{1}{2{,}81 + \sqrt{2{,}81^2 - 2{,}11^2}} = 0{,}21$$

$$\sigma_{c,0,d} = k_{cy}f_{c,o,g,k}$$ $$\sigma_{c,0,d} = 0{,}21 * 21{,}5 = 4{,}60\frac{N}{mm^2}$$

$$N_{max,fi} = A_{fi}\sigma_{c,0,d}10^{-3}$$ $$N_{max,fi} = 2704 * 4{,}60 * 10^{-3} = 12{,}4\ kN$$

Table. Glulam column with one layer of GtF 15 according to 2020 version of Eurocode after 30 minutes of fire

Cross-section / mm x mm	80x80	200x200	400x400
Protective layer	GtF15	GtF15	GtF15
Result / kNm	**12.4**	**603**	**2975.2**
Required time / min	30	30	30
Strength class	GL24h	GL24c	GL24c
L / m	3	3	3
b / mm	80	200	400
h / mm	80	200	400
$\gamma_{M,fi}$	1	1	1
k_{fi}	1.15	1.15	1.15
$f_{c,0,g,k}$ / kN/mm^2	21.5	21.5	21.5
$k_{mod,fi}$	1	1	1
$f_{d,fi}$ / kN/mm^2	24.725	24.725	24.725
β_0 / mm/min	0.65	0.65	0.65
h_p / mm	15	15	15
k_2	0.73	0.73	0.73
k_3	2	2	2
k_4	1	1	1
k_n	1.08	1.08	1.08
$k_n\beta_0$ / mm/min	0.70	0.70	0.70
$k_2k_n\beta_0$ / mm/min	0.51	0.51	0.51
$k_3k_n\beta_0$ / mm/min	1.40	1.40	1.40
$k_4k_n\beta_0$ mm/min	0.702	0.702	0.702
$t_{f,degr}$ / min	51	51	51
$t_{prot,i}$ / min	30	30	30
t_{ch} / min	30	30	30
t_f / min	51	51	51
t_a / min	61.14	61.14	61.14
$d_{char,n\ tf}$ / mm	10.76	10.76	10.76
$d_{char,n\ ta}$ / mm	25.00	25.00	25.00
$d_{char,n\ t}$ / mm	0.00	0.00	0.00
d_0 / mm	14.00	14.00	14.00
d_{ef} / mm	14.00	14.00	14.00
b_{fi} / mm	52.00	172.00	372.00
h_{fi} / mm	52.00	172.00	372.00
A_{fi} / mm^2	2704	29584	138384
$N_{max,fi}$ / kN	66.8	731.4	3421.5
I / mm^4	609301.3	72934421	1.6E+09
i / mm	15.01111	49.65212	107.3872
l_0 / mm	2100	2100	2100
λ_y	139.8964	42.29426	19.55541

Table continues

$E_{0,05}$ / kN/mm^2	9600	9600	9600
$\lambda_{rel,y}$	2.107368	0.637111	0.294578
k_y	2.810868	0.719811	0.543117
k_{cy}	0.214088	0.948048	1.000594
$\sigma_{c,0,d}$ / kN/mm^2	4.602899	20.38303	21.5
$N_{max,fi}$ / kN	12.44624	603.0116	2975.256

Table. Glulam column with one layer of GtF 15 according to 2020 version of Eurocode after 60 minutes of fire

Cross-section / mm x mm	80x80	200x200	400x400
Protective layer	GtF15	GtF15	GtF15
Result / kNm	**0**	**264.9**	**2207.9**
Required time / min	60	60	60
Strength class	GL24h	GL24c	GL24c
L / m	3	3	3
b / mm	80	200	400
h / mm	80	200	400
$\gamma_{M,fi}$	1	1	1
k_{fi}	1.15	1.15	1.15
$f_{c,0,g,k}$ / kN/mm^2	21.5	21.5	21.5
$k_{mod,fi}$	1	1	1
$f_{d,fi}$ / kN/mm^2	24.725	24.725	24.725
β_0 / mm/min	0.65	0.65	0.65
h_p / mm	15	15	15
k_2	0.73	0.73	0.73
k_3	2	2	2
k_4	1	1	1
k_n	1.08	1.08	1.08
$k_n\beta_0$ / mm/min	0.70	0.70	0.70
$k_2k_n\beta_0$ / mm/min	0.51	0.51	0.51
$k_3k_n\beta_0$ / mm/min	1.40	1.40	1.40
$k_4k_n\beta_0$ mm/min	0.702	0.702	0.702
$t_{f,degr}$ / min	51	51	51
$t_{prot,i}$ / min	30	30	30
t_{ch} / min	30	30	30
t_f / min	51	51	51
t_a / min	61.14	61.14	61.14
$d_{char,n\ tf}$ / mm	10.76	10.76	10.76
$d_{char,n\ ta}$ / mm	25.00	25.00	25.00
$d_{char,n\ t}$ / mm	23.40	23.40	23.40
d_0 / mm	16.00	16.00	16.00
d_{ef} / mm	39.40	39.40	39.40

Table continues

b_{fi} / mm	1.20	121.20	321.20
h_{fi} / mm	1.20	121.20	321.20
A_{fi} / mm^2	1.451254	14690.57	103172.4
$N_{max,fi}$ / kN	0	363.2	2550.9
I / mm^4	0.175511	17984415	8.87E+08
i / mm	0.353565	34.98878	92.7238
l_0 / mm	2100	2100	2100
λ_y	5939.503	60.01925	22.64791
$E_{0,05}$ / kN/mm^2	9600	9600	9600
$\lambda_{rel,y}$	89.47131	0.904116	0.341163
k_y	4007.517	0.938919	0.560254
k_{cy}	0.000125	0.838798	0.995366
$\sigma_{c,0,d}$ / kN/mm^2	0.002683	18.03415	21.40037
$N_{max,fi}$ / kN	3.89E-06	264.932	2207.928

Table. Glulam column with one layer of GtF 15 according to 2020 version of Eurocode after 90 minutes of fire

Cross-section / mm x mm	80x80	200x200	400x400
Protective layer	GtF15	GtF15	GtF15
Result / kNm	**0**	**58.5**	**1637**
Required time / min	90	90	90
Strength class	GL24h	GL24c	GL24c
L / m	3	3	3
b / mm	80	200	400
h / mm	80	200	400
$\gamma_{M,fi}$	1	1	1
k_{fi}	1.15	1.15	1.15
$f_{c,0,g,k}$ / kN/mm^2	21.5	21.5	21.5
$k_{mod,fi}$	1	1	1
$f_{d,fi}$ / kN/mm^2	24.725	24.725	24.725
β_0 / mm/min	0.65	0.65	0.65
h_p / mm	15	15	15
k_2	0.73	0.73	0.73
k_3	2	2	2
k_4	1	1	1
k_n	1.08	1.08	1.08
$k_n\beta_0$ / mm/min	0.70	0.70	0.70
$k_2k_n\beta_0$ / mm/min	0.51	0.51	0.51
$k_3k_n\beta_0$ / mm/min	1.40	1.40	1.40
$k_4k_n\beta_0$ mm/min	0.702	0.702	0.702
$t_{f,degr}$ / min	51	51	51
$t_{prot,i}$ / min	30	30	30

Table continues

t_{ch} / min	30	30	30
t_f / min	51	51	51
t_a / min	61.14	61.14	61.14
$d_{char,n\ tf}$ / mm	10.76	10.76	10.76
$d_{char,n\ ta}$ / mm	25.00	25.00	25.00
$d_{char,n\ t}$ / mm	45.26	45.26	45.26
d_0 / mm	16.00	16.00	16.00
d_{ef} / mm	61.26	61.26	61.26
b_{fi} / mm	0.00	77.48	277.48
h_{fi} / mm	0.00	77.48	277.48
A_{fi} / mm^2	0	6003.513	76996.45
$N_{max,fi}$ / kN	0	148.4	1903.7
I / mm^4	0	3003514	4.94E+08
i / mm	0	22.36722	80.10225
l_0 / mm	2100	2100	2100
λ_y	0	93.88737	26.21649
$E_{0,05}$ / kN/mm^2	9600	9600	9600
$\lambda_{rel,y}$	0	1.414298	0.394919
k_y	0.485	1.555834	0.582727
k_{cy}	1.030928	0.453679	0.988902
$\sigma_{c,0,d}$ / kN/mm^2	21.5	9.754094	21.26139
$N_{max,fi}$ / kN	0	58.55883	1637.051

Appendix 15 Calculations of tested beams

Table Data of tests

NR	1	2	3	4	5	6	7	8	9	10
h / mm	254	256	256	253	253	217	362	600	599	600
b / mm	157	158	158	158	157	157	120	140	140	140
Protective layer	none	none	none	none	none	none	none	none	none	none
Strength class	GL24h	GL36h	GL36h	GL24h	GL36h	GL36h	GL24h	GL24h	GL32h	GL32h
t / min	52	49.25	68.88	48.1	58.28	44.4	48.2	32	24.5	13.5
M / kNm	16.4	20.7	13.9	16	21	14.5	23	97	124.5	124.5

An example for following calculations can be seen in Appendix 2.

Table Reference calculations based on EN 1995-1-2:2004 with strength class bending strength

NR	1	2	3	4	5	6	7	8	9	10
$\gamma_{M,fi}$	1	1	1	1	1	1	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	36	36	24	36	36	24	24	32	32
$k_{mod,fi}$	1	1	1	1	1	1	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	41.4	41.4	27.6	41.4	41.4	27.6	27.6	36.8	36.8
β_n	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
$d_{char,n}$ / mm	36.4	34.48	48.22	33.67	40.8	31.08	33.74	22.4	17.15	9.45
k_0	1	1	1	1	1	1	1	1	1	1
d_0 / mm	7	7	7	7	7	7	7	7	7	7
d_{ef} / mm	43.4	41.48	55.22	40.67	47.8	38.08	40.74	29.4	24.15	16.45
b_{fi} / mm	70.2	75.05	47.56	76.66	61.4	80.84	38.52	81.2	91.7	107.1
h_{fi} / mm	210.6	214.5	200.8	212.3	205.2	178.9	321.3	570.6	574.9	583.6
W_{fi} / mm^3	518923	575646	319572	576024	430926	431313	521685	316205	430713	431313
$M_{max,fi}$ / kNm	14.3	23.8	13.2	15.8	17.8	17.8	18.2	121.6	185.8	223.6
M-$M_{max,fi}$ / kNm	2.1	-3.1	0.7	0.2	3.2	-3.3	4.8	-24.6	-61.3	-99.1

Table Refecernce calculations based on EN 1995-1-2:2004 with mean bending strength

NR	1	2	3	4	5	6
$\gamma_{M,fi}$	1	1	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	31.2	39.8	39.8	31.2	39.8	39.8
$k_{mod,fi}$	1	1	1	1	1	1
$f_{d,fi}$ / N/mm^2	35.88	45.77	45.77	35.88	45.77	45.77
β_n	0.7	0.7	0.7	0.7	0.7	0.7
$d_{char,n}$ / mm	36.4	34.48	48.22	33.67	40.8	31.08

Table continued

NR	1	2	3	4	5	6
k_0	1	1	1	1	1	1
d_0 / mm	7	7	7	7	7	7
d_{ef} / mm	43.4	41.48	55.22	40.67	47.8	38.08
b_{fi} / mm	70.2	75.05	47.56	76.66	61.4	80.84
h_{fi} / mm	210.6	214.5	200.8	212.3	205.2	178.9
W_{fi} / mm^3	518923	575646	319572	576024	430926	431313
$M_{max,fi}$ / kNm	18.6	26.3	14.6	20.6	19.7	19.7
M-$M_{max,fi}$ / kNm	-2.2	-5.6	-0.7	-4.6	1.3	-5.2

An example for following calculations can be seen in Appendix 9.

Table Reference calculations based on EN 1995-1-2:2020 with strength class bending strength

NR	1	2	3	4	5	6	7	8	9	10
$\gamma_{M,fi}$	1	1	1	1	1	1	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	36	36	24	36	36	24	24	32	32
k_Θ	1	1	1	1	1	1	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	41.4	41.4	27.6	41.4	41.4	27.6	27.6	36.8	36.8
β_0	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65
k_n	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08
β_n	0.702	0.702	0.702	0.702	0.702	0.702	0.702	0.702	0.702	0.702
$d_{char,n}$ / mm	36.5	34.57	48.36	33.77	40.91	31.17	33.84	22.46	17.2	9.477
d_0 / mm	7	7	10	7	7	7	7	7	7	7
d_{ef} / mm	43.5	41.57	58.36	40.77	47.91	38.17	40.84	29.46	24.2	16.48
b_{fi} / mm	69.99	74.85	41.29	76.47	61.17	80.66	38.33	81.07	91.6	107
h_{fi} / mm	210.5	214.4	197.6	212.2	205.1	178.8	321.2	570.5	574.8	583.5
W_{fi} / mm^3	516874	573608	268805	574057	428802	429939	519640	265909	428589	429939
$M_{max,fi}$ / kNm	14.2	23.7	11.1	15.8	17.7	17.7	18.1	121.3	185.6	223.5
M-$M_{max,fi}$ / kNm	2.2	-3	2.8	0.2	3.3	-3.2	4.9	-24.3	-61.1	-99

Table Reference calculations based on EN 1995-1-2:2020 with strength class bending strength and d_0=10mm

NR	1	2	3	4	5	6	7	8	9	10
$\gamma_{M,fi}$	1	1	1	1	1	1	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	24	36	36	24	36	36	24	24	32	32
k_Θ	1	1	1	1	1	1	1	1	1	1
$f_{d,fi}$ / N/mm^2	27.6	41.4	41.4	27.6	41.4	41.4	27.6	27.6	36.8	36.8
β_0	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65	0.65

Table continued

NR	1	2	3	4	5	6	7	8	9	10
k_n	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08	1.08
β_n	0.702	0.702	0.702	0.702	0.702	0.702	0.702	0.702	0.702	0.702
$d_{char,n}$ / mm	36.5	34.57	48.36	33.77	40.91	31.17	33.84	22.46	17.2	9.477
d_0 / mm	10	10	10	10	10	10	10	10	10	10
d_{ef} / mm	46.5	44.57	58.36	43.77	50.91	41.17	43.84	32.46	27.2	19.48
b_{fi} / mm	63.99	68.85	41.29	70.47	55.17	74.66	32.33	75.07	85.6	101
h_{fi} / mm	207.5	211.4	197.6	209.2	202.1	175.8	318.2	567.5	571.8	580.5
W_{fi} / mm^3	459192	512968	268805	514164	375510	384718	519640	313938	428589	429939
$M_{max,fi}$ / kNm	12.6	21.2	11.1	14.1	15.5	15.9	15	111.2	171.6	208.8
M-$M_{max,fi}$ / kNm	3.8	-0.5	2.8	1.9	5.5	-1.4	8	-14.2	-47.1	-84.3

Table Refecernce calculations based on EN 1995-1-2:2020 with mean bending strength

NR	1	2	3	4	5	6
$\gamma_{M,fi}$	1	1	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15	1.15	1.15
$f_{m,g,k}$	31.2	39.8	39.8	31.2	39.8	39.8
k_Θ	1	1	1	1	1	1
$f_{d,fi}$	35.88	45.77	45.77	35.88	45.77	45.77
β_0	0.65	0.65	0.65	0.65	0.65	0.65
k_n	1.08	1.08	1.08	1.08	1.08	1.08
β_n	0.702	0.702	0.702	0.702	0.702	0.702
$d_{char,n}$ / mm	36.5	34.57	48.36	33.77	40.91	31.17
d_0 / mm	7	7	10	7	7	7
d_{ef} / mm	43.5	41.57	58.36	40.77	47.91	38.17
b_{fi} / mm	69.99	74.85	41.29	76.47	61.17	80.66
h_{fi} / mm	210.5	214.4	197.6	212.2	205.1	178.8
W_{fi} / mm^3	516874	573608	268805	574057	428802	429939
$M_{max,fi}$ / kNm	18.5	26.2	12.3	20.5	19.6	19.6
M-$M_{max,fi}$ / kNm	-2.1	-5.5	1.6	-4.5	1.4	-5.1

Table Refecernce calculations based on EN 1995-1-2:2020 with mean bending strength and d_0=10mm

NR	1	2	3	4	5	6
$\gamma_{M,fi}$	1	1	1	1	1	1
k_{fi}	1.15	1.15	1.15	1.15	1.15	1.15
$f_{m,g,k}$ / N/mm^2	31.2	39.8	39.8	31.2	39.8	39.8
k_Θ	1	1	1	1	1	1
$f_{d,fi}$ / N/mm^2	35.88	45.77	45.77	35.88	45.77	45.77
β_0	0.65	0.65	0.65	0.65	0.65	0.65
k_n	1.08	1.08	1.08	1.08	1.08	1.08
β_n	0.702	0.702	0.702	0.702	0.702	0.702
$d_{char,n}$ / mm	36.5	34.57	48.36	33.77	40.91	31.17
d_0 / mm	10	10	10	10	10	10
d_{ef} / mm	46.5	44.57	58.36	43.77	50.91	41.17
b_{fi} / mm	63.99	68.85	41.29	70.47	55.17	74.66
h_{fi} / mm	207.5	211.4	197.6	209.2	202.1	175.8
W_{fi} / mm^3	459192	512968	268805	514164	375510	384718
$M_{max,fi}$ / kNm	16.4	23.4	12.3	18.4	17.1	17.6
$M-M_{max,fi}$ / kNm	0	-2.7	1.6	-2.4	3.9	-3.1

Appendix 16 Interview with Alar Just

1. When did the revision of Eurocode 5 start?

In 2012.

2. Who is working on the revision of EN 1995-1-2 and where?

The revision is done in CEN TC250 SC5 WG4 (Fire) by project team 4 – Andrea Frangi, Alar Just, Jouni Hakkarainen, Norman Werther and Joachim Schmid.

3. How far gone is the process?

The first draft was released in May 2019, the second in May 2020 and the third in October 2020. The final version will be published in May 2021.

4. When will the official release be?

After balloting, comments, reviewing and synchronising with other parts of Eurocode, it is expected in 2025.

5. What are the main changes?

In some parts, the terms and symbols have changed a little bit. A concept of charring phases is being introduced. In the start time of charring, the start time of charring Separating Function Method is used. Also, the failure times of GtF have been added and the depth of the zero-strength layer has been increased to avoid overestimating the fire resistance.

6. Has the Reduced Properties Method also been revised?

No, TC250 SC5 WG4 made the decision not to revise this.

Appendix 17 Comparison of fire resistance test of column with the calculation models (Confidential)

Unfortunately, there are not as many published test results regarding glulam columns with all the necessary data for the reference calculations as there are about glulam beams. However, in this thesis, one glulam column from confidential reference is calculated and analysed. This clause of the thesis is not public and is removed from the published version of the thesis.

The parameters of the column are shown in Table 0.1. The end conditions are pin-pin.

Table 0.1 Parameters of the tested column

h / mm	400
b / mm	400
L / mm	3100
Protective layer	none
Strength class	GL24h
e / mm	6
t / min	104
N / kN	1020

The results of calculations are shown in Table 0.2.

Table 0.2 Calculation results of column

	Result / kN	Percentage of test result
Test	1020	100%
EC5:2004	1595	156%
EC5:2004 with combined compression and bending	1513	148%
EC5: 2004 with buckling	1287.4	126%
EC5:2020	1360	133%
EC5:2020 with combined compression and bending	1285	126%
EC5:2020 with buckling	1073.4	105%

As seen in Table 0.2, the failure of the column is caused by buckling. The difference between the results of EN 1995-1-2:2004 and EN 1995-1-2:2020 is significant and the calculations based on EN 1995-1-2:2020 are closer to the test result than calculations based on EN 1995-1-2:2004. As mentioned above, the difference between the results of calculations of columns are due to differences in the zero-strength layer.

In 2006, comprehensive tests were conducted to estimate the depth of the zero-strength layer on compressed members. The tests lasted between 13 and 52 minutes [5]. The results are shown in Table 0.3.

Table 0.3 Values for zero-strength layer

Zero-strength layers in compression	mm
EC5:2004	7
EC5:2020 before 60 minutes of fire	14
$d_{0,min}$ [5]	15,5
$d_{0,max}$ [5]	23,3
$d_{0,mean}$ [5]	18,1

As can be seen above, the test results show an even deeper zero-strength layer than it is in the revised EN 1995-1-2. The reference calculations were done according to EN 1995-1-2:2020 with an increased depth in the zero-strength layer and the results are presented in Table 0.4.

Table 0.4 Calculation results of column with increased depth of zero-strength layer

Calculation method	d0 / mm	Result / kN	Percentage of test result
Test		1020	100%
EC5:2020 with compression only	16	1360	133%
EC5:2020 with combined compression and bending	16	1285	126%
EC5:2020 with buckling	16	1073.4	105%
EC5:2020 with compression only	18	1311.4	129%
EC5:2020 with combined compression and bending	18	1237	121%
EC5:2020 with buckling	18	1028.642	101%

As can be seen in Table 0.4, the increased depth of the zero-strength layer gave a very close result to the test result. However, one column is not enough to decide as to whether, increasing the depth of the zero-strength layer is necessary.

CALCULATIONS

Table. Parameters of column and test results

NR		1
h	mm	400
b	mm	400
L		3100
Protective layer		-
Strength class		GL24h
e	mm	6
t	min	104
N	kN	1020

Example for calculations in the following table is in Appendix 5.

Table. Calculations according to EN 1995-1-2:2004

$\gamma M,fi$		1
k_{fi}		1.15
$f_{c,0,g,k}$	N/mm^2	24
$k_{mod,fi}$		1
$f_{d,fi}$	N/mm^2	27.6
β_n		0.7
$d_{char,n}$	mm	72.8
k_0		1
d_0	mm	7
d_{ef}	mm	79.8
b_{fi}	mm	240.4
h_{fi}	mm	240.4
A_{fi}	mm^2	57792.16
$N_{max,fi}$	kN	1595
I	mm^4	278327813.1
i	mm	69.39750236
l_0	mm	3100
λ_y		44.67019554
$E_{0,05}$		9600
$\lambda_{rel,y}$		0.710948243
k_y		0.773271114
k_{cy}		0.928151276
$\sigma_{c,0,d}$	N/mm^2	22.27563061
$N_{max,fi}$	kN	1287.356809

Calculations in the following table are performed according to Chapter 5. The compressive force is found by trial and error method to satisfy equation (5.15).

Table. Calculations of combined bending and axial compression

N	kN	1513
e	mm	6
My	kNm	9.078
W	mm^3	2315539.211
$\sigma_{m,y,d}$	N/mm^2	3.920469132
$f_{m,y,d}$	N/mm^2	27.6
$f_{c,0,g,k}$	N/mm^2	27.6
k_m		0.7
$\sigma_{c,0,d}$	N/mm^2	26.18002165

$$\left(\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right)^2 + \frac{\sigma_{m,y,d}}{f_{m,y,d}} = 0.9992 \leq 1$$

Example for calculations in the following table is in Appendix 12. Although, the member is both compressed and bended, the depth of the zero-strength layer is taken equal with the depth of the zero-strength layer for compressed member, as it is larger than depth of the zero-strength layer for bended member and therefore gives more conservative results.

Table. Calculations according to EN 1995-1-2:2020

$\gamma_{M,fi}$		1
k_{fi}		1.15
$f_{c,0,g,k}$	N/mm^2	24
k_Θ		1
$f_{d,fi}$	N/mm^2	27.6
β_0		0.65
k_n		1.08
β_n		0.702
$d_{char,n}$	mm	73.008
d_0	mm	16
d_{ef}	mm	89.008
b_{fi}	mm	221.984
h_{fi}	mm	221.984
A_{fi}	mm^2	49276.9
$N_{max,fi}$	kN	1360
I	mm4	202351042.1
i	mm	64.08125864
l_0	mm	3100

Table continues

λ_y		48.37607852
$E_{0,05}$		9600
$\lambda_{rel,y}$		0.769929202
k_y		0.819891949
k_{cy}		0.907664654
$\sigma_{c,0,d}$	N/mm2	21.78395171
$N_{max,fi}$	kN	1073.44561

Table. Calculations of combined bending and axial compression

N	kN	1285
e	mm	6
My	kNm	7.71
W	mm^3	1823113.756
$\sigma_{m,y,d}$	N/mm^2	4.229028481
$f_{m,y,d}$	N/mm^2	27.6
$f_{c,0,g,k}$	N/mm^2	27.6
k_m		0.7
$\sigma_{c,0,d}$	N/mm^2	26.07712742

$$\left(\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right)^2 + \frac{\sigma_{m,y,d}}{f_{m,y,d}} = 0.9999 \leq 1$$

Table. Calculations according to EN 1995-1-2:2020 with increased depth of the zero-strength layer

$\gamma_{M,fi}$		1
k_{fi}		1.15
$f_{c,0,g,k}$	N/mm^2	24
k_Θ		1
$f_{d,fi}$	N/mm^2	27.6
β_0		0.65
k_n		1.08
β_n		0.702
$d_{char,n}$	mm	73.008
d_0	mm	18
d_{ef}	mm	91.008
b_{fi}	mm	217.984
h_{fi}	mm	217.984
A_{fi}	mm^2	47517
$N_{max,fi}$	kN	1311.4
I	mm4	188155632.8
i	mm	62.9265766
l_0	mm	3100

Table continues

λ_y		49.2637637
$E_{0,05}$		9600
$\lambda_{rel,y}$		0.784057151
k_y		0.831575665
k_{cy}		0.901994571
$\sigma_{c,0,d}$	N/mm2	21.64786971
$N_{max,fi}$	kN	1028.641825

Table. Calculations of combined bending and axial compression

N	kN	1237
e	mm	6
My	kNm	7.422
W	mm^3	1726325.169
$\sigma_{m,y,d}$	N/mm^2	4.299305908
$f_{m,y,d}$	N/mm^2	27.6
$f_{c,0,g,k}$	N/mm^2	27.6
k_m		0.7
$\sigma_{c,0,d}$	N/mm^2	26.03278827

$$\left(\frac{\sigma_{c,0,d}}{f_{c,0,d}}\right)^2 + \frac{\sigma_{m,y,d}}{f_{m,y,d}} = 0.9987 \leq 1$$