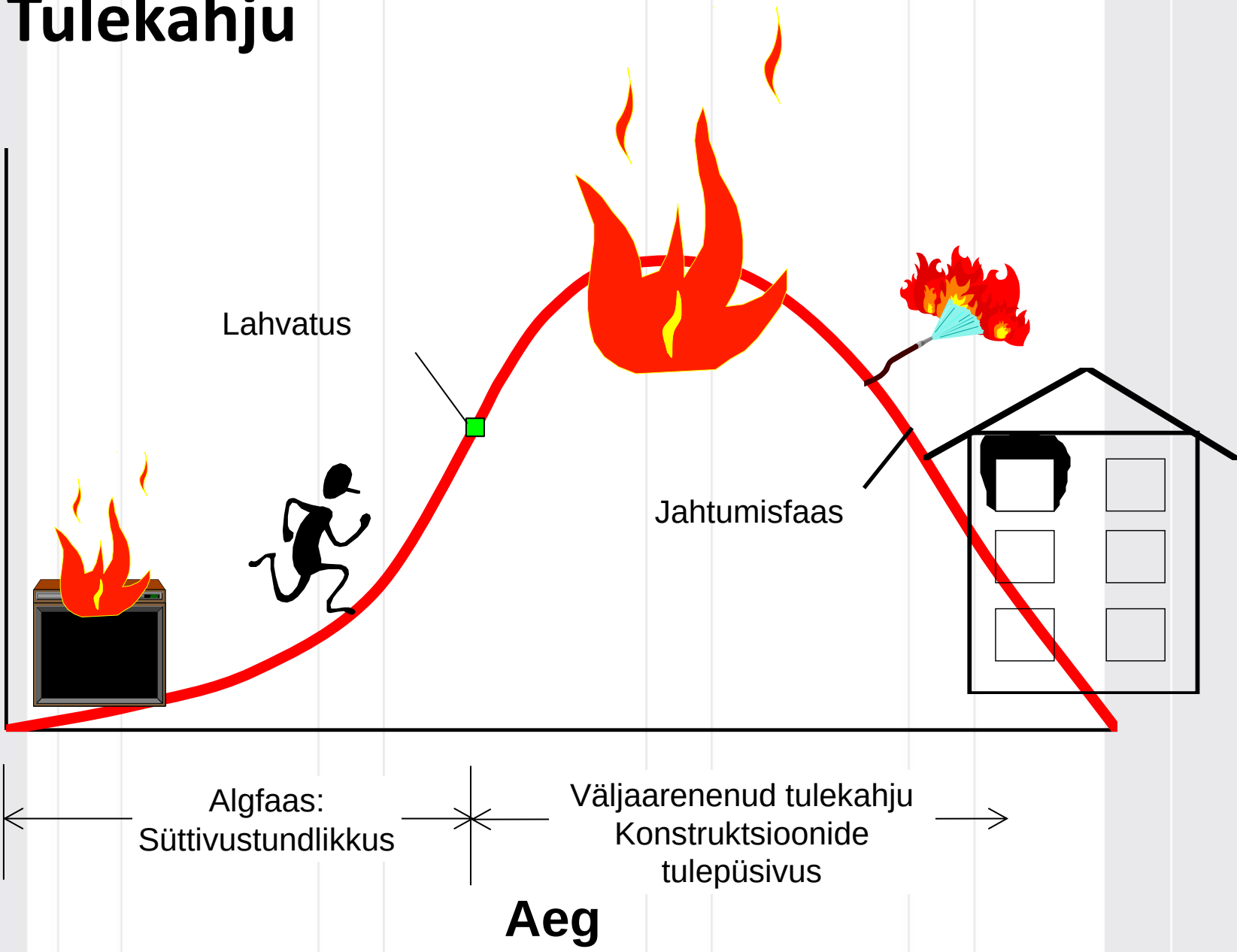
# Puitkonstruktsioonide tulepüsivus

# Kandevõime

Alar Just

18. oktoober 2016

# Tulekahju

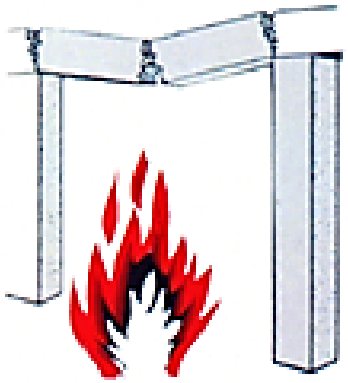

Temperatuur
Lahvatus
Jahtumisfaas
Algfaas:
Süttivustundlikkus
Väljaarenenud tulekahju
Konstruktsioonide
tulepüsivus
Aeg

*Michael Green:*

# Puidu kandevôime tules

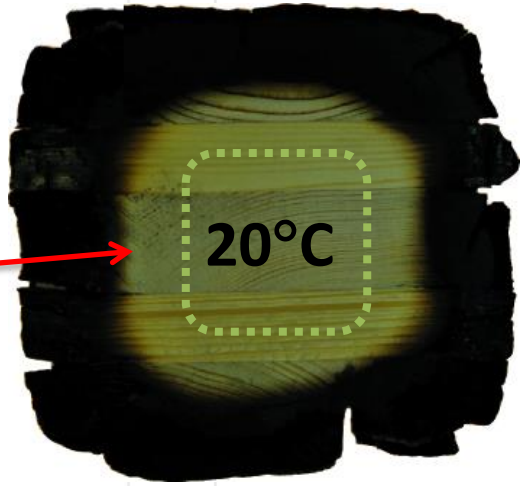
I. Elemendi söestumine (ristlôike vähenemine)

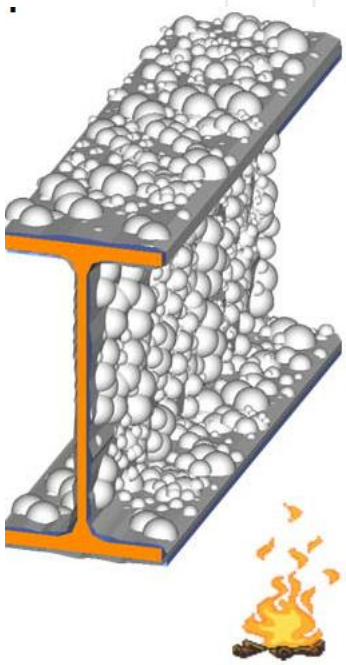
II. Elemendi kuumenemine (tugevuse vähenemine)



Kandevôime R

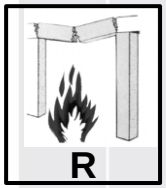
# Puidu söestumine




BELARUS
BELARUS
WELCOME
MALA
SELAMAT DATANG
WELCOME
MALAYSIA
MILANO2015
EXPO
MALAYSIA

# Ehituskonstruktsiooni tulepüsivus




**Võimalused Euroopas:**

"Ohutuse nõue"
(CPR/rahvuslikud nõuded)

**Konstruktsiooni täismõõdus katsetamine**
*Liigitus vastavalt EN 13501-2*

**Konstruktsiooni projekteerimine vastavalt standarditele**
*Näiteks vastavalt EN 1995-1-2*

Konstruktsiooni tuleohutu kasutamine

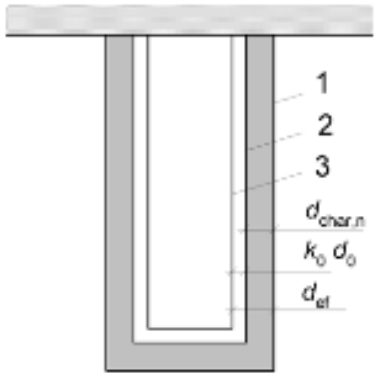
# Projekteerimine

**Tulekatsed**

- Ajamahukad ning kulukad
- Vajalik iga konstruktsiooni jaoks eraldi
- Konstruktsiooni optimeerimine

**Arvutusmeetodid**

- Ajasäästlikud ning odavad
- Tulemused konservatiivsed võrreldes katsetega



# Puitkonstruktsioonid tules

”Suured ristlôiked”

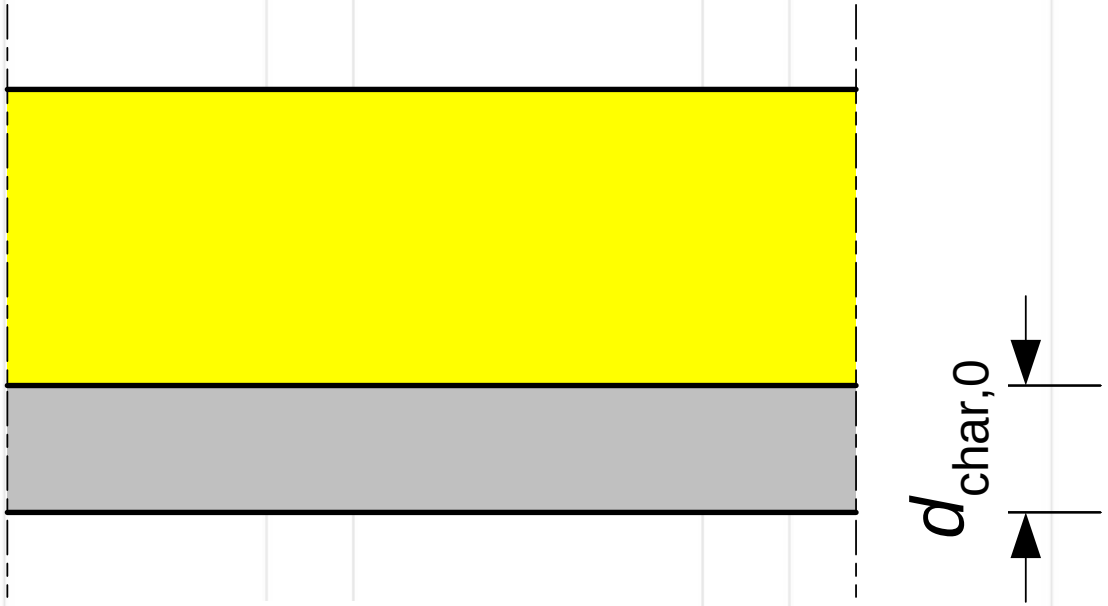
Postid, talad, plaadid

”Väiksed ristlôiked”


Puitkarkassseinad ja -vahelaed

# POSTID JA TALAD, PLAADID

# Söestumine

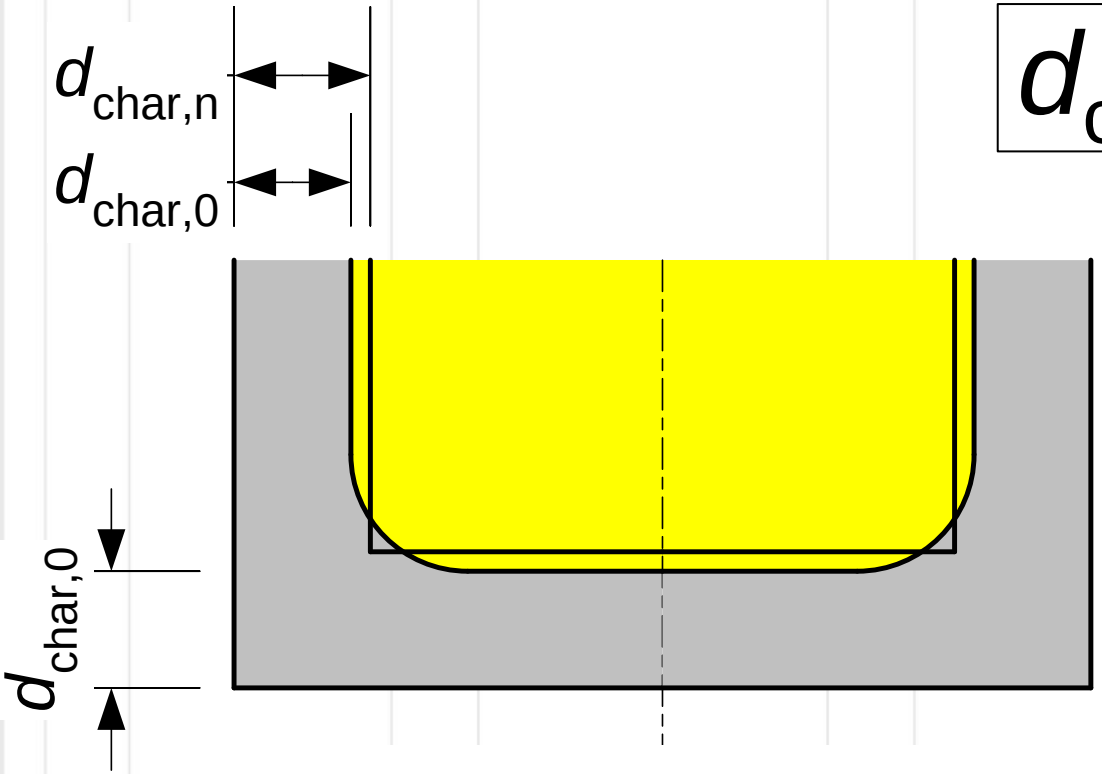



puitplaat

Ühemõõtmeline söestumine:
söestumismäär $\beta_0$

$$d_{char,0} = \beta_0 \, t$$

# Söestumine




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

liimpuittala

Tinglik söestumine: söestumismäär $\beta_n$

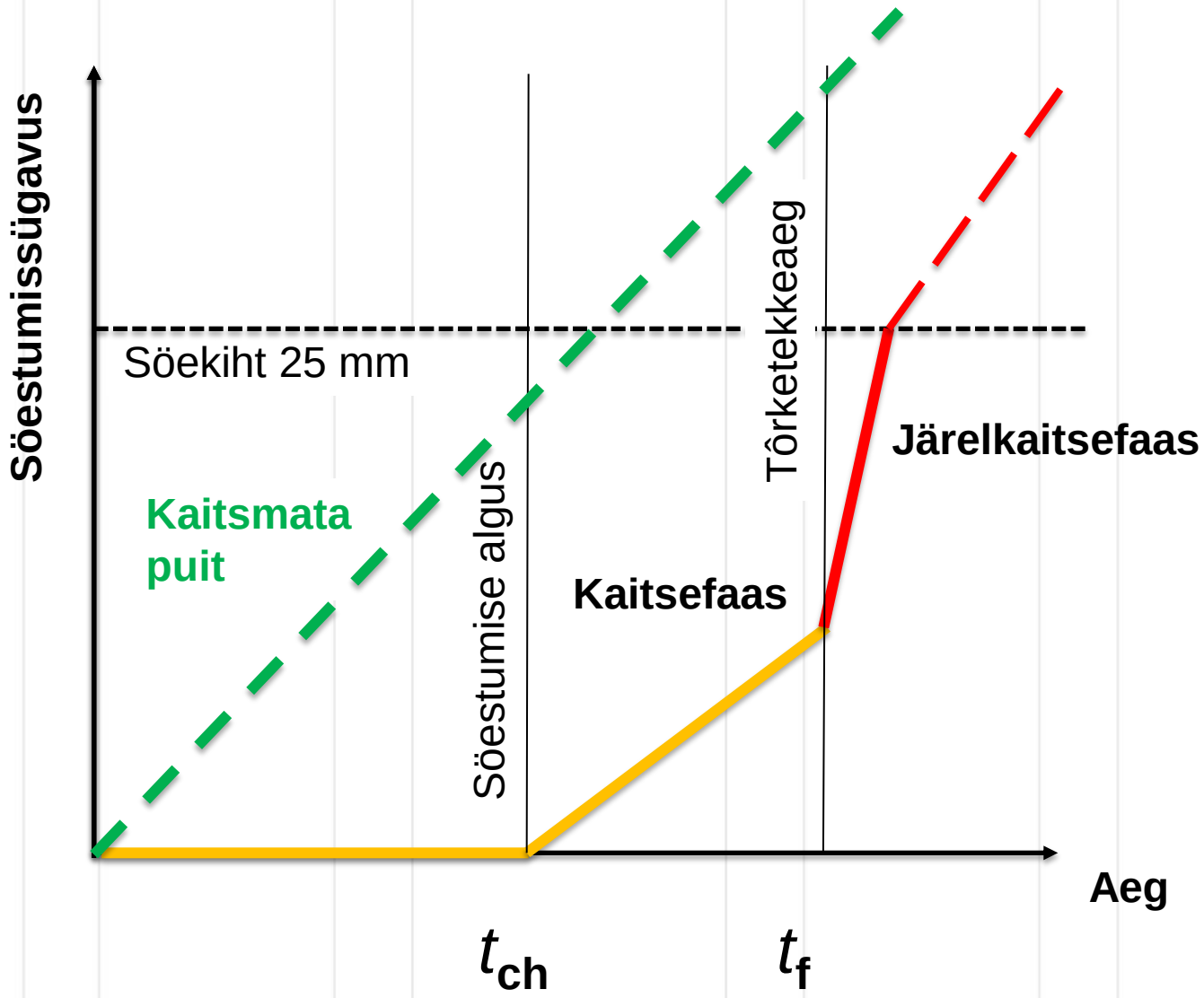
Ekvivalentne ristkülikuline jääkristlõige

# Söestumiskiirused

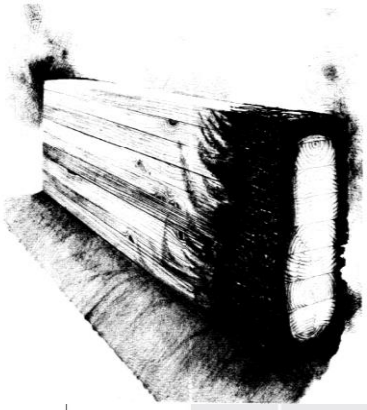
EN 1995-1-2
Tabel 3.1

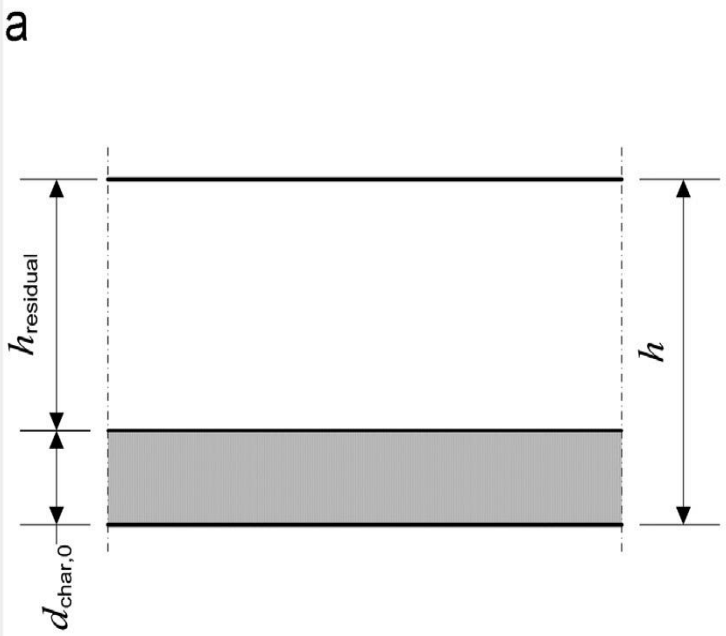
| | $\beta_o$, mm/min | $\beta_n$ mm/min |
|---|---|---|
| **Okaspuit** | | |
| Liimpuit | 0,65 | 0,7 |
| Saepuit | 0,65 | 0,8 |
| **Lehtpuit** | | |
| $\rho > 290$ kg/m$^3$ | 0,65 | 0,7 |
| $\rho > 450$ kg/m$^3$ | 0,5 | 0,55 |
| **Spoonliimpuit** | **0,65** | **0,7** |

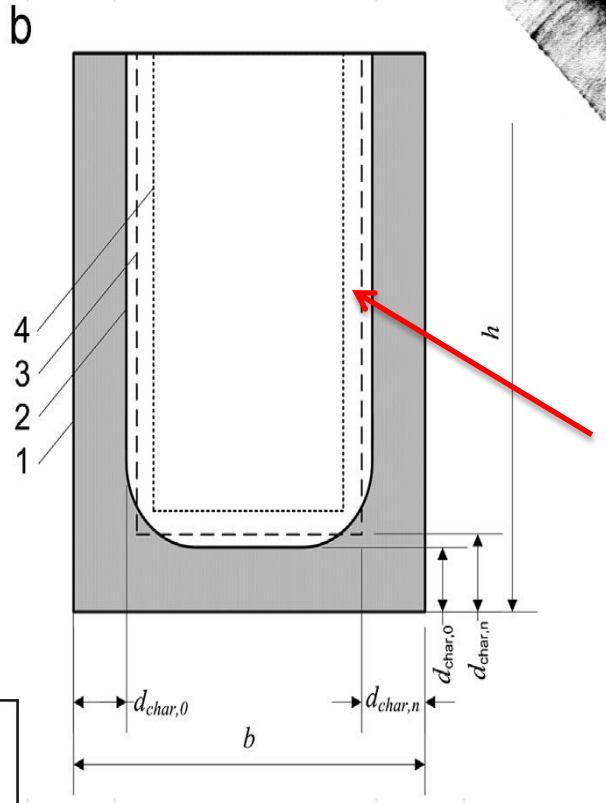
# Puidu söestumine



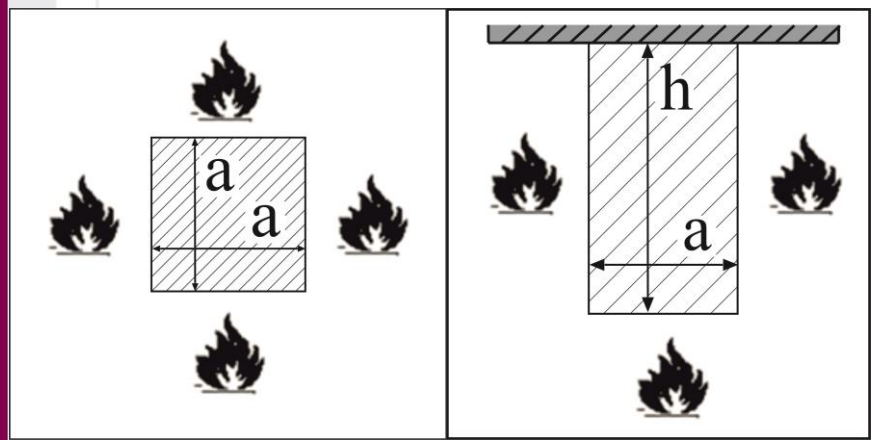
# Efektiivristlôikemeetod





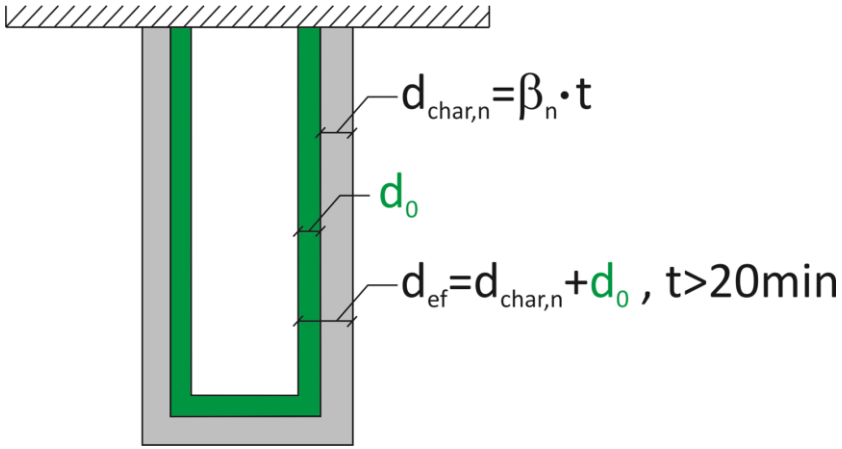



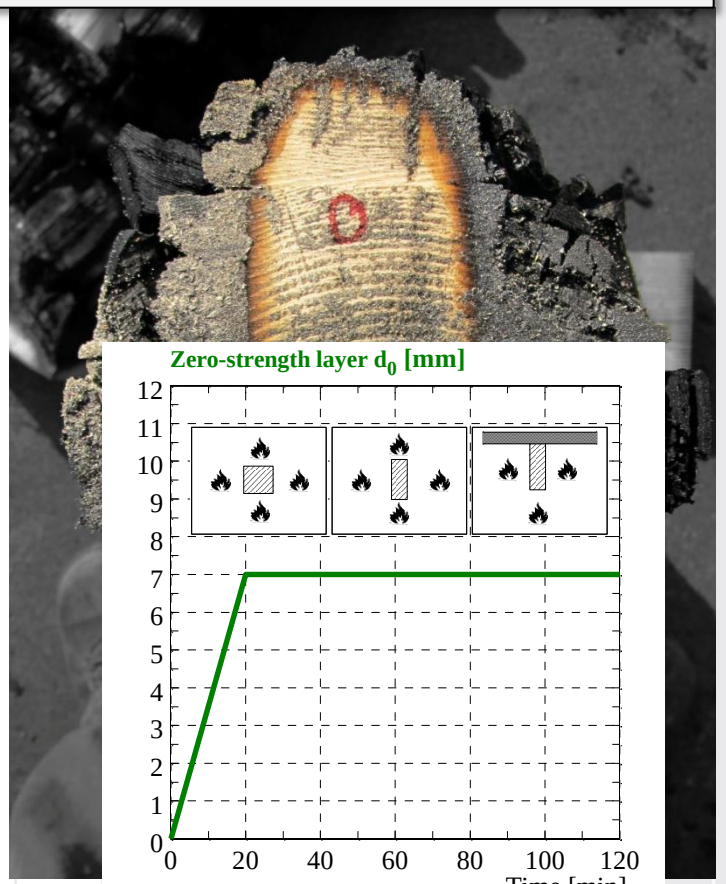

$d_o$



# Efektiivristlôikemeetod

$d_0$ kompenseerib puidu tugevuse muutumise kôrgetel temperatuuridel



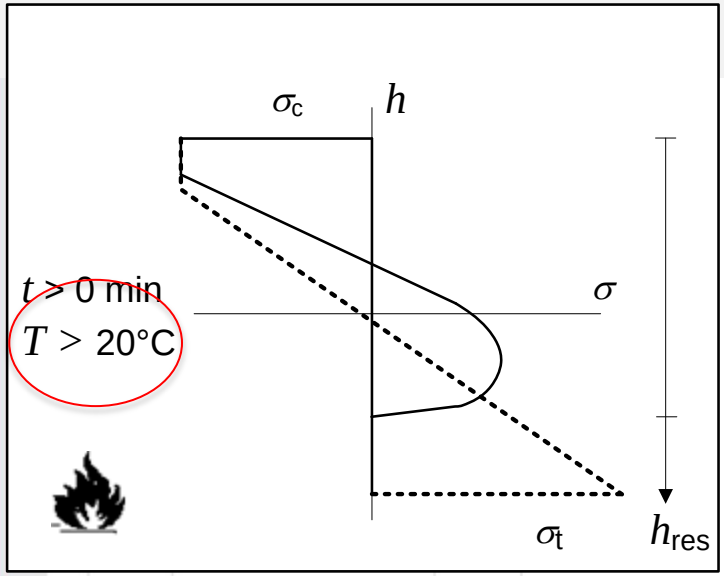



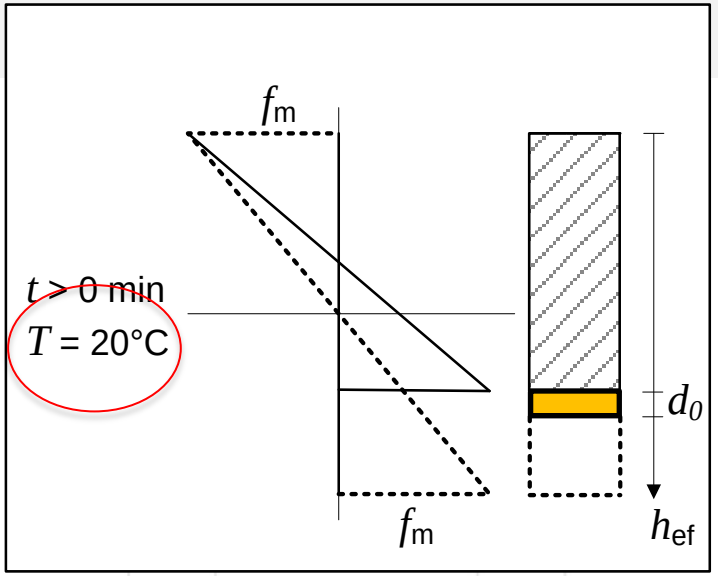

**EN 1995-1-2** -> $d_0$=7mm

# Efektiivristlôikemeetod

## Pôhimôte

- Kuuma ja külma ristlôike vôrdlus
- Vôrdne kandevôime
- Erinevus -> **null-tugevusega kiht $d_o$**



# Arvutustugevus tulekahjuolukorras

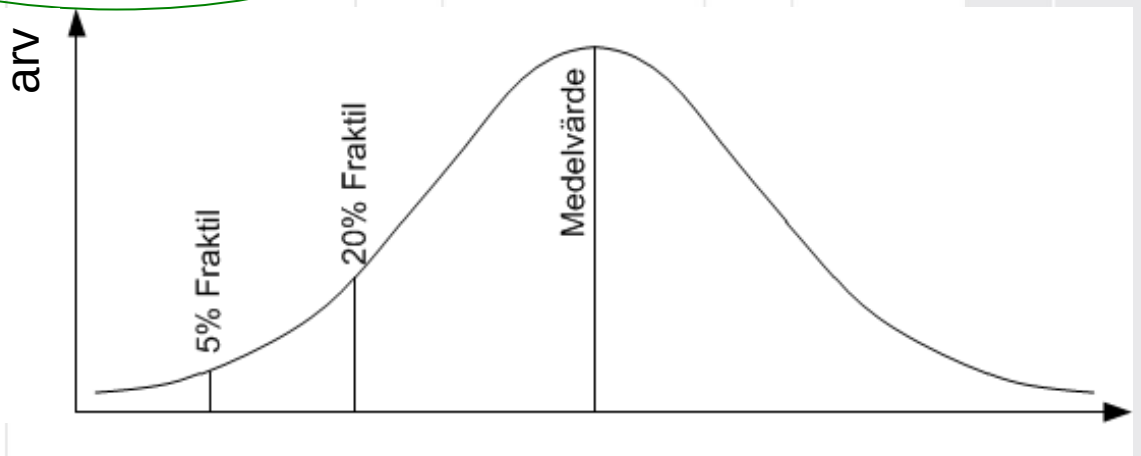
$$f_{d,fi} = k_{mod,fi} \frac{f_{20}}{\gamma_{M,fi}}$$

tugevuse 20 % fraktiil

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

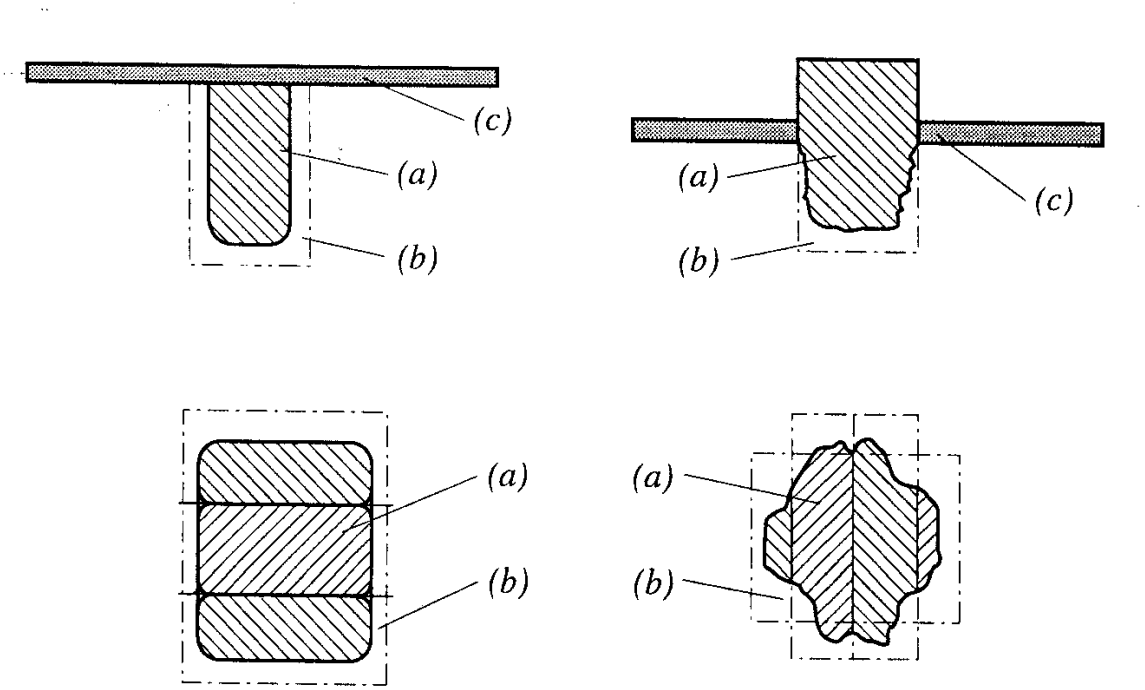
$k_{fi}$ väärtused

| | |
|---|---|
| Saepuit | 1,25 |
| Lamell-liimpuit | 1,15 |
| Spoonliimpuit | 1,1 |

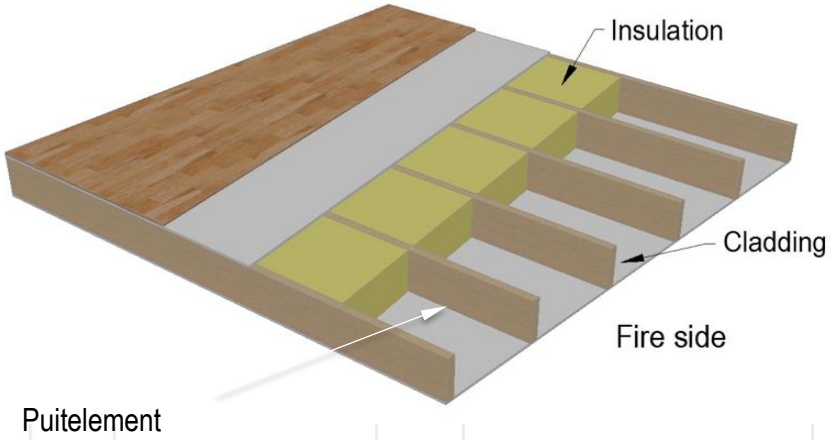


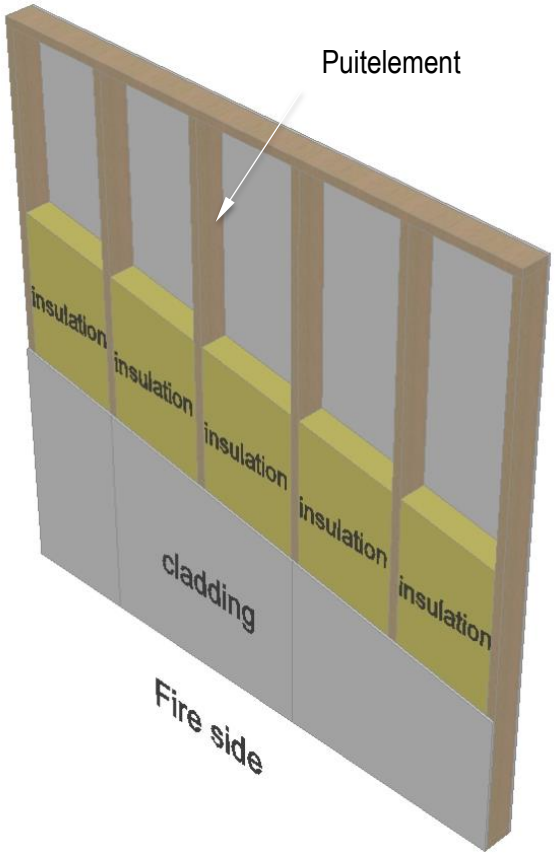
# Efektiivristlõike meetod

• Teostatakse kandevõime kontroll leitud tugevuste, koormuste, ristlõigetega



# Puitkarkass-seinad ja -vahelaed

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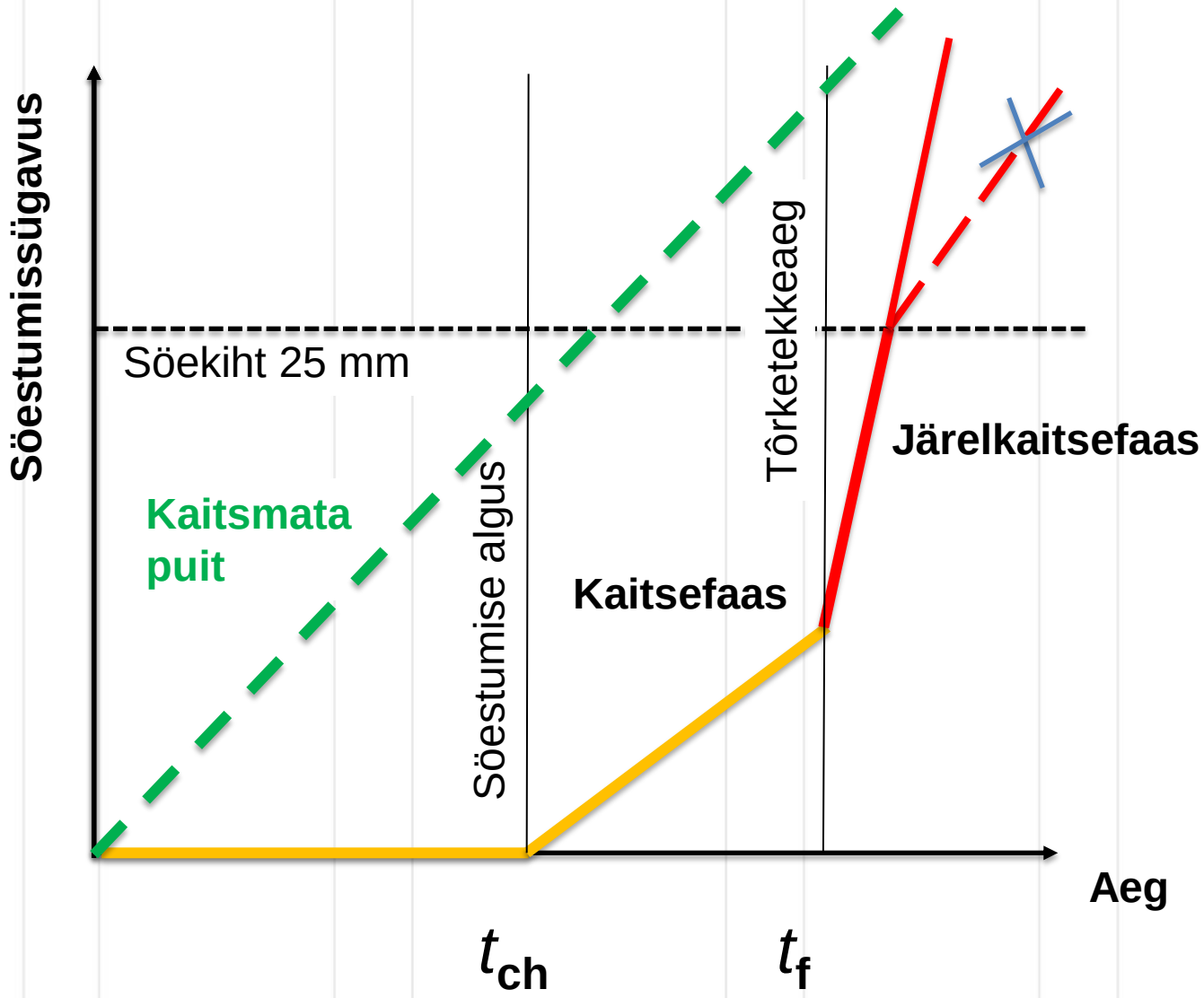
# Puidu söestumine



# Puidupôhised plaadid

Söestumise algusaeg

$$t_{ch} = h_p / \beta_{0,\rho,t}$$

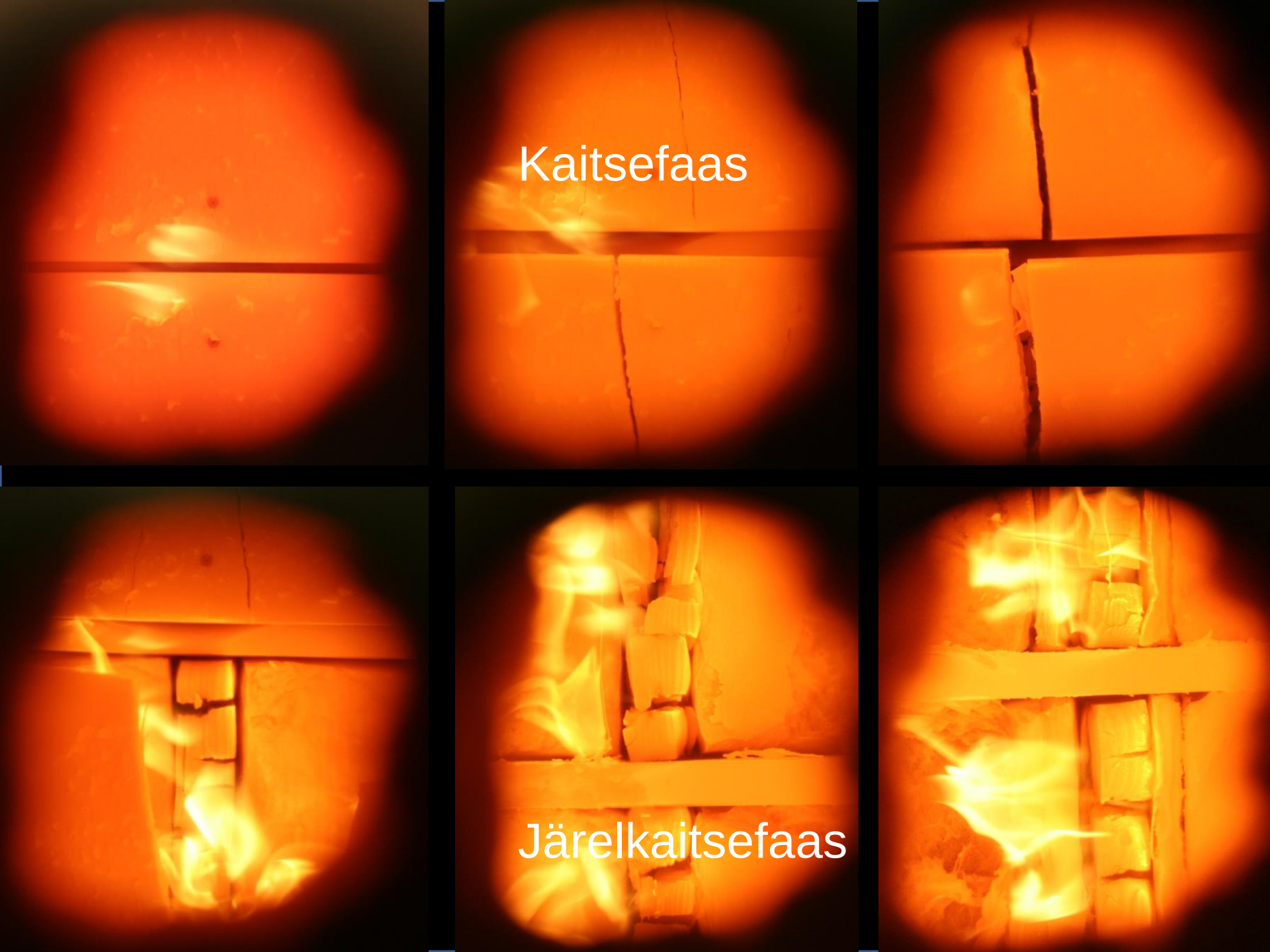
$h_p$ - plaadi paksus

$$\beta_{0,\rho,t} = \beta_0 \; k_\rho \; k_h$$

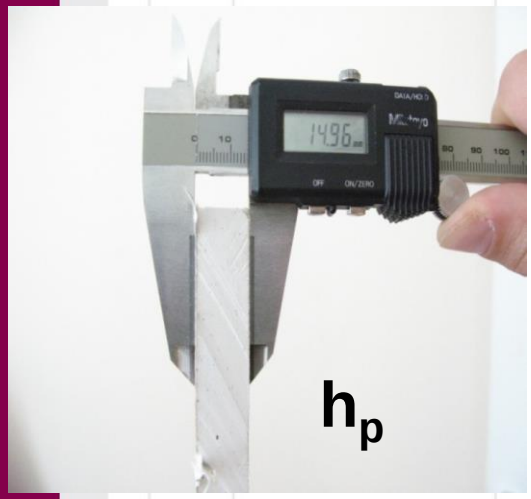
with

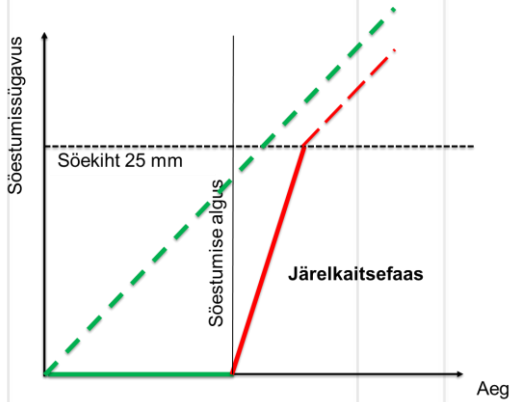
$$k_\rho = \sqrt{\frac{450}{\rho_k}}$$

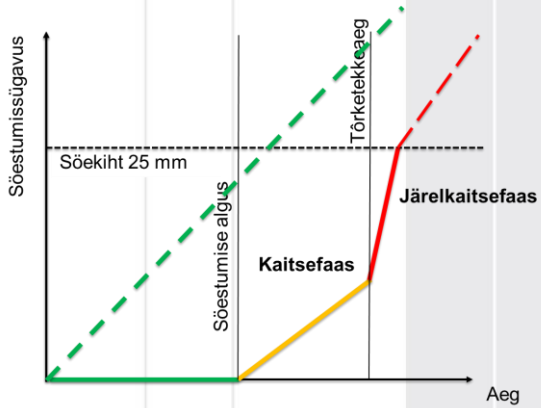
$$k_h = \sqrt{\frac{20}{h_p}}$$


Kaitsefaas
Järelkaitsefaas

# Kipsplaatide kaitsevôime




**Tüüp A**

**Tüüp F**

**EN 1995-1-2**

Söestumise algus

Tôrketekke-aeg

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

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

$t_f=t_{ch}$

**Katsetamine**

# Kipsplaadid

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

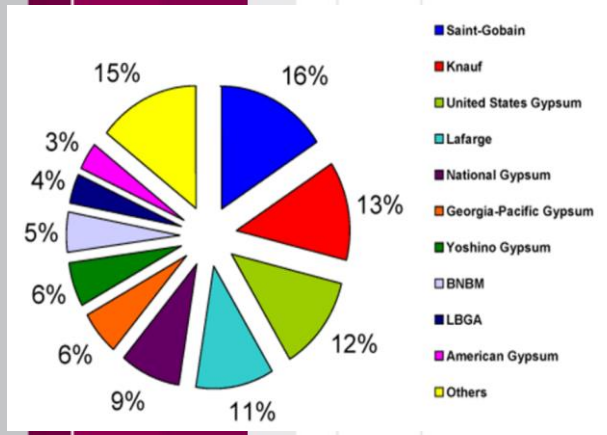
2 kihti, tüüp F

$h_p = h_{p,1} + 0{,}8h_{p,2}$

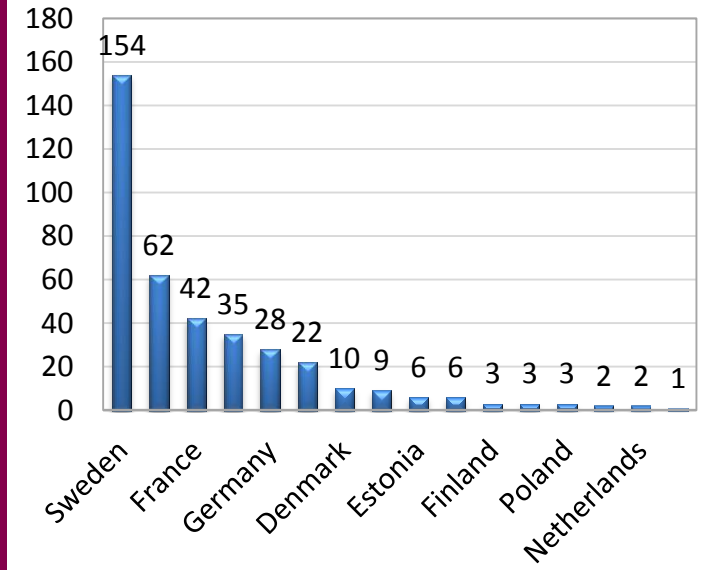
2 kihti, tüüp A

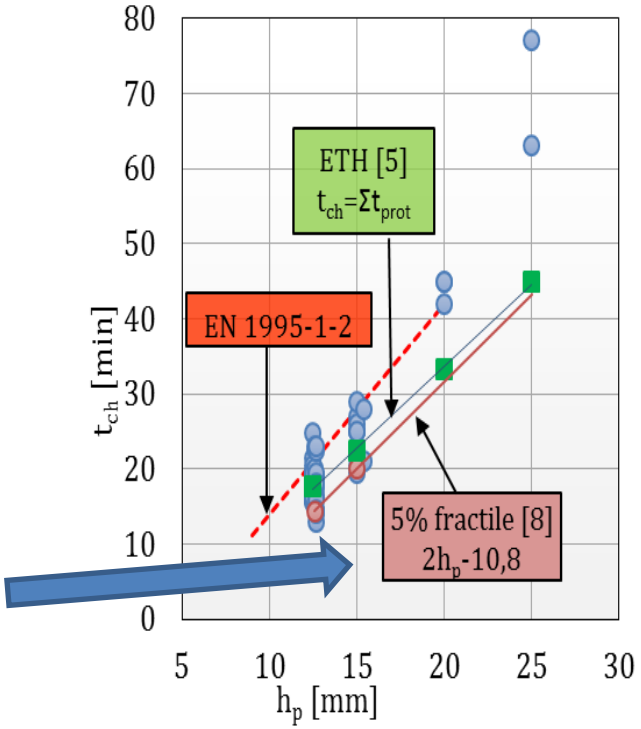
$h_p = h_{p,1} + 0{,}5h_{p,2}$

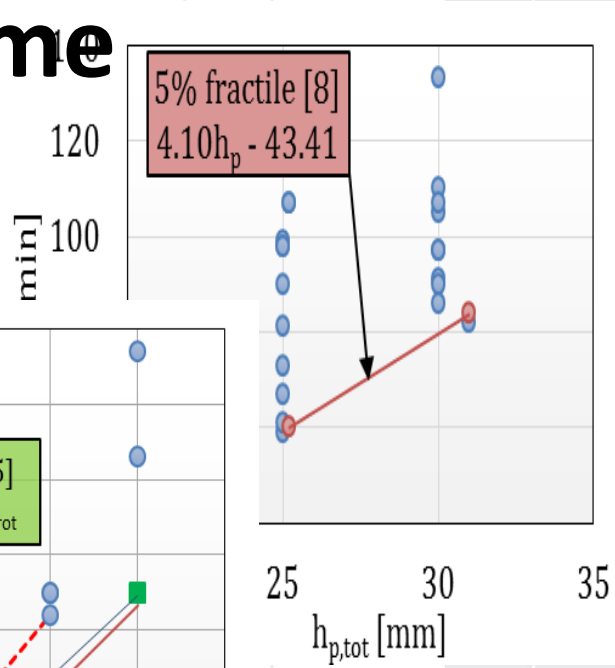
# Kipsplaatide kaitsevõime




***Täismõõdus tulekatsed***

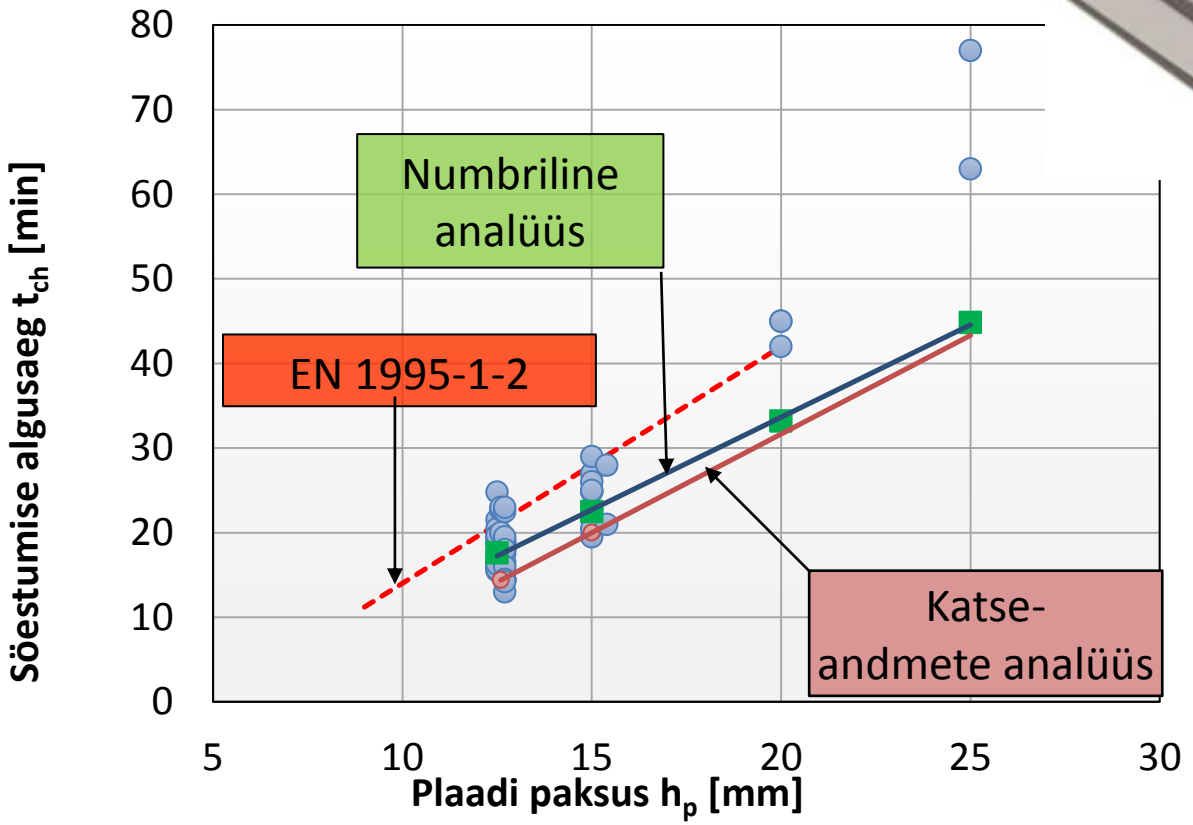



*Kraudok, K. (2015) Protective effect of gypsum plasterboards for the fire design of timber structures. Master thesis. TUT. Tallinn, Estonia.*

# Kipsplaatide kaitsevõime




**Kipsplaadid, 1 kiht**

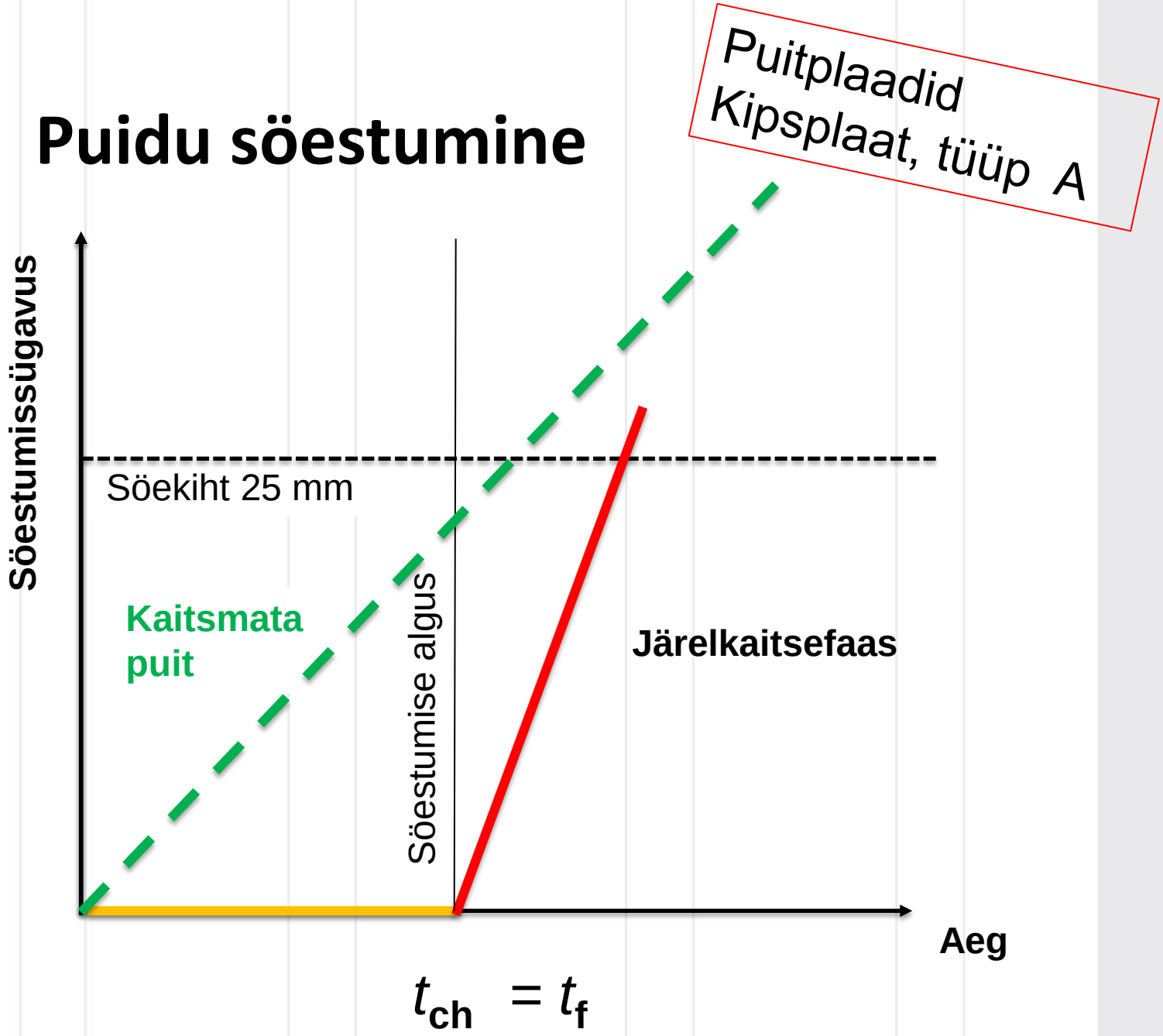
*Kraudok, K. (2015) Protective effect of gypsum plasterboards for the fire design of timber structures. Master thesis. TUT. Tallinn, Estonia.*

# Tõrketekkeaeg

Kinnitite väljatômme

$$t_f = t_{ch} + \frac{l_f - l_{a,min} - h_p}{k_s \, k_2 \, k_n \, k_j \, \beta_0}$$

# Puidu söestumine

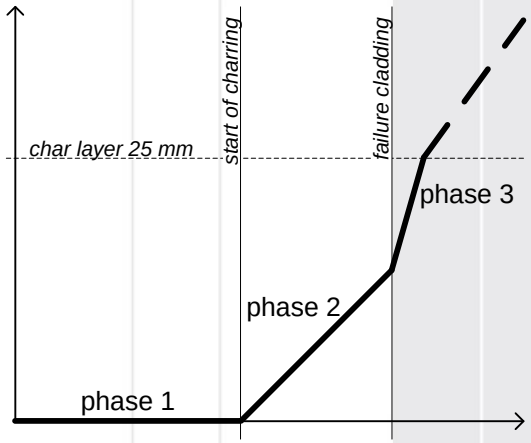


# Tõrketekkeaeg

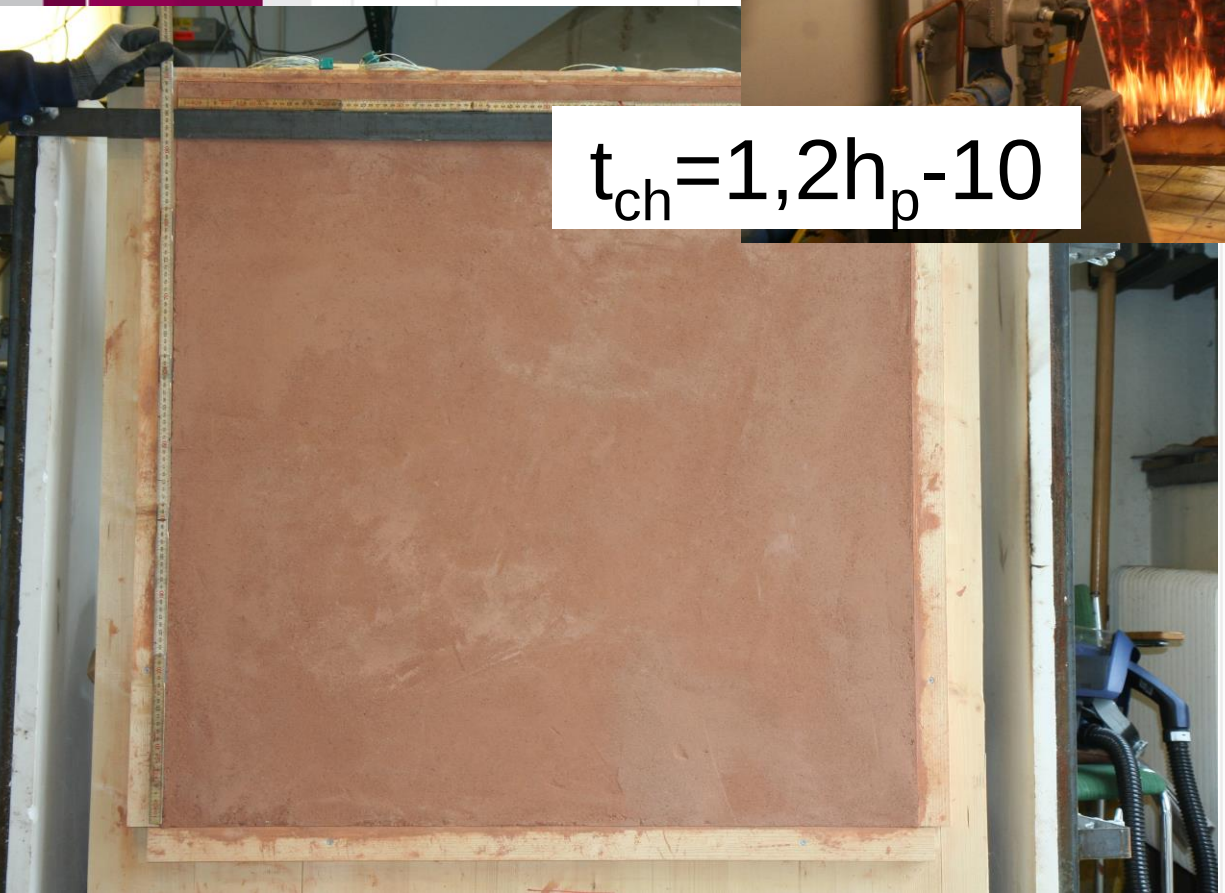
## Söestumine järelkaitsefaasis

$$\beta = k_3 \beta_0$$

$$k_3 = 2$$



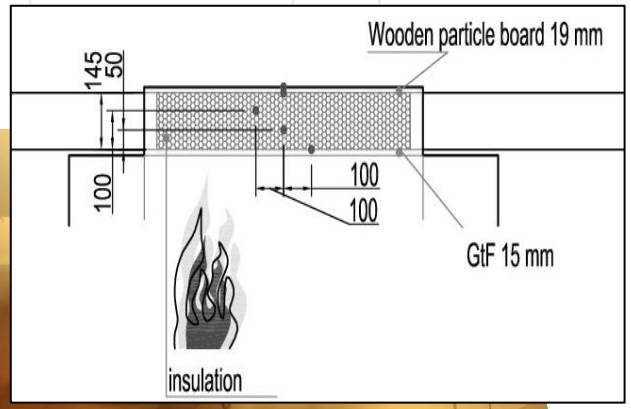
# Savikrohv



$t_{ch}=1,2h_p-10$

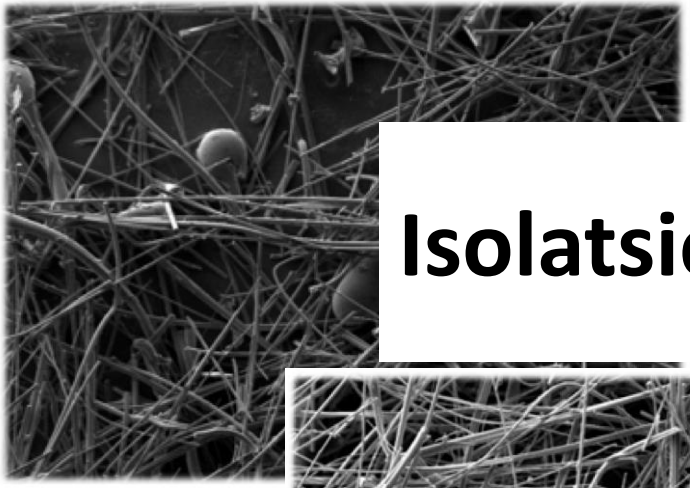

*Liblik, J. (2015) Protective effect of clay plaster for the fire design of timber structures. Master thesis. TUT. Tallinn, Estonia.*

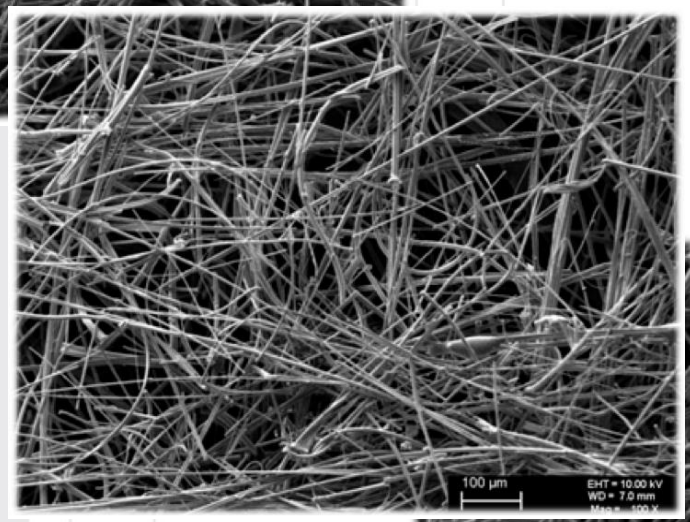
# “Uued” materjalid

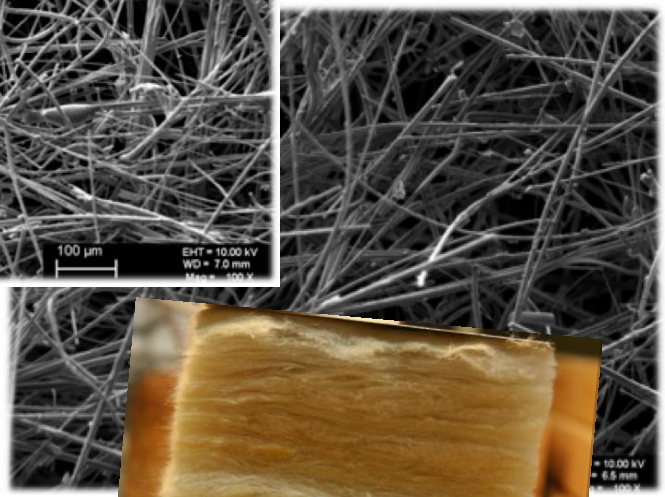





# Isolatsioonimaterjalid

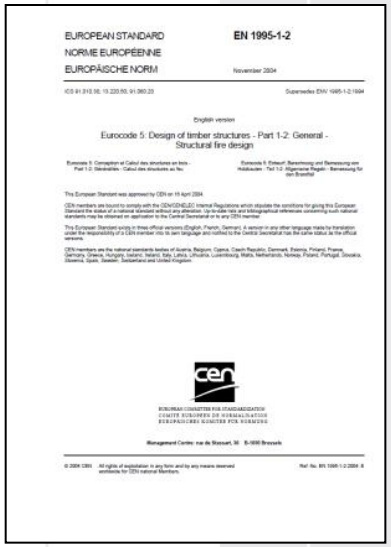




# Mineraalvill

- **Eurokoodeks 5 teeb vahet “kivivilla” ja “klaasvilla” vahel.**

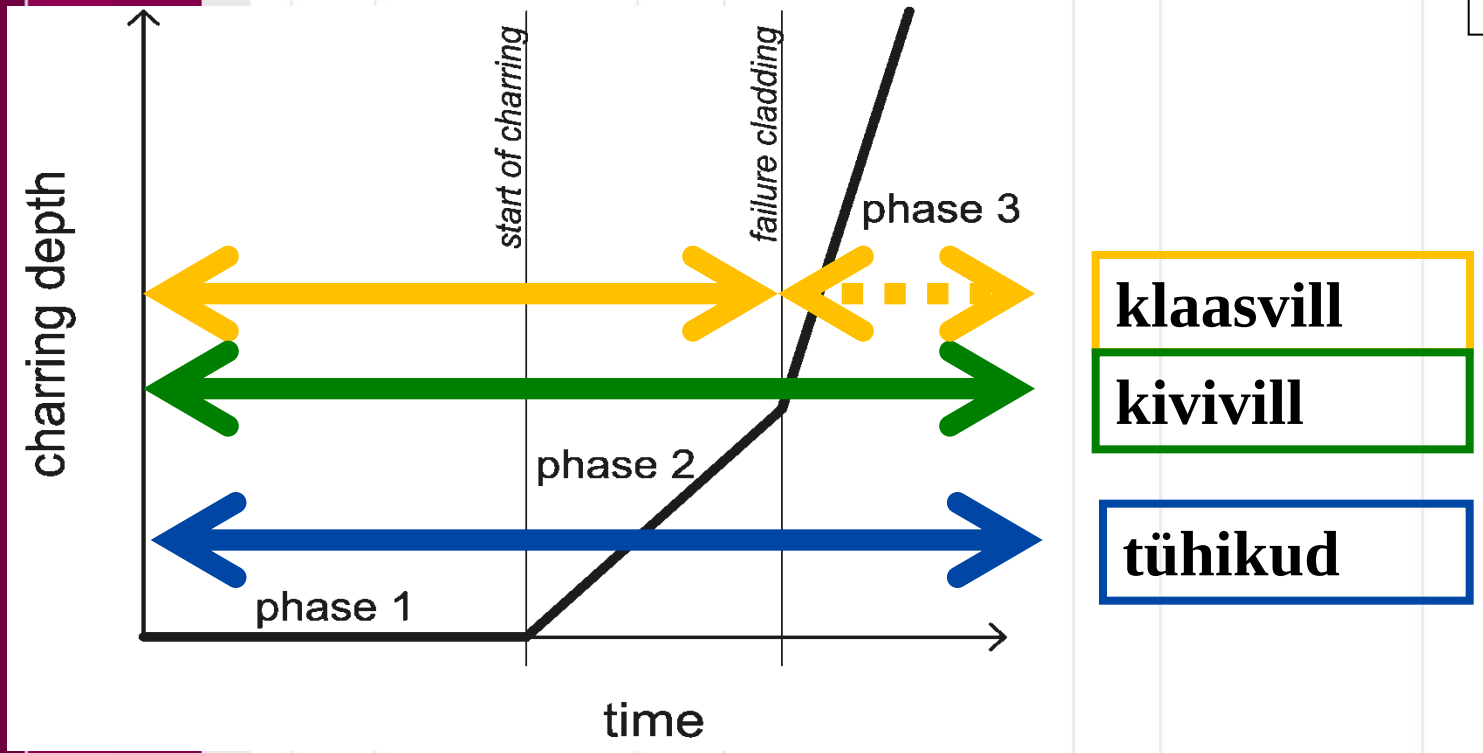

EUROPEAN STANDARD
NORME EUROPÉENNE
EUROPÄISCHE NORM

EN 1995-1-2

November 2004

English version

Eurocode 5: Design of timber structures - Part 1-2: General - Structural fire design

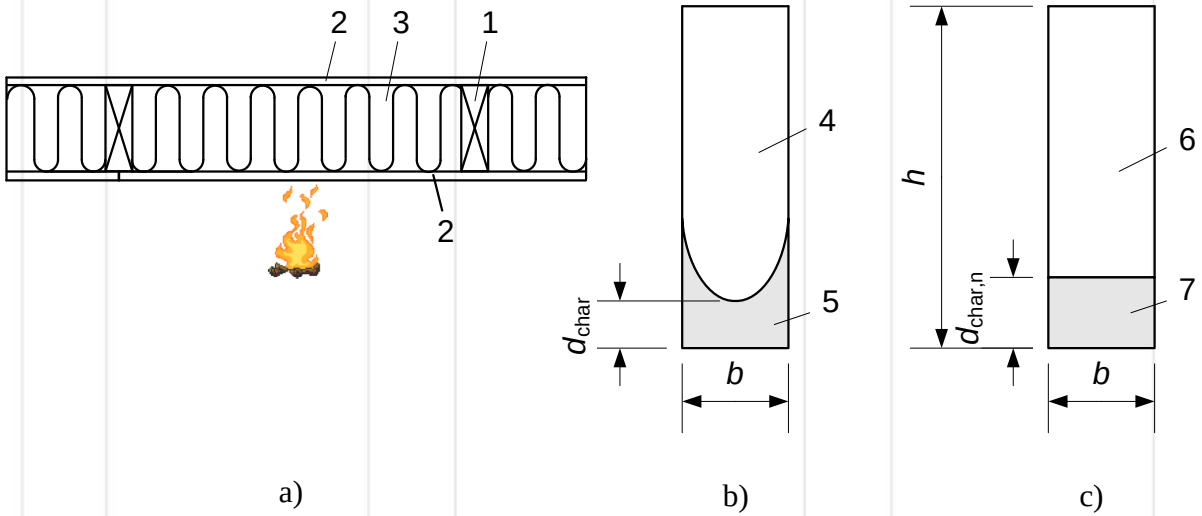



**klaasvill**

**kivivill**

**tühikud**

# Vähendatud tugevusomaduste meetod



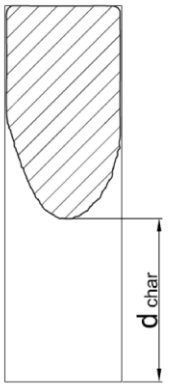

a) b) c)

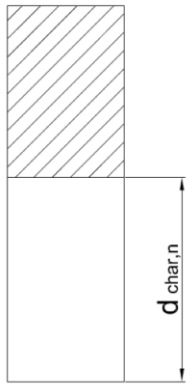
$$k_{mod,fm,fi} = a_0 - a_1 \frac{d_{char,n}}{h}$$

$$k_{mod,E,fi} = b_0 - b_1 \frac{d_{char,n}}{h}$$

1 Puitelement
2 Katteplaat
3 Isolatsioon
4 Jääkristlõige (tegelik)
5 Söestumissügavus (tegelik)
6 Ekvivalentne ristkülikuline ristlõige
7 Effektiivne söestumissügavus

# Söestumismäär




Kaitsefaas

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

$$\beta_n = k_2 \, k_s \, k_n \, \beta_0$$

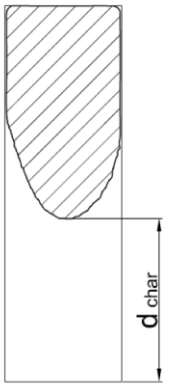
$k_2$ – isolatsioonitegur

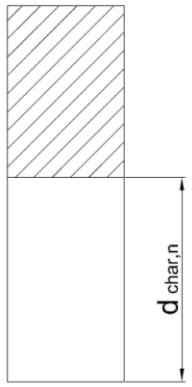
Nii kivi- kui klaasvilla puhul

$k_2 = 1{,}05 - 0{,}0073 h_p$ ilma vuugita

$k_2 = 0.96 - 0{,}0037 h_p$ vuugiga

# Söestumismäär




Järelkaitsefaas

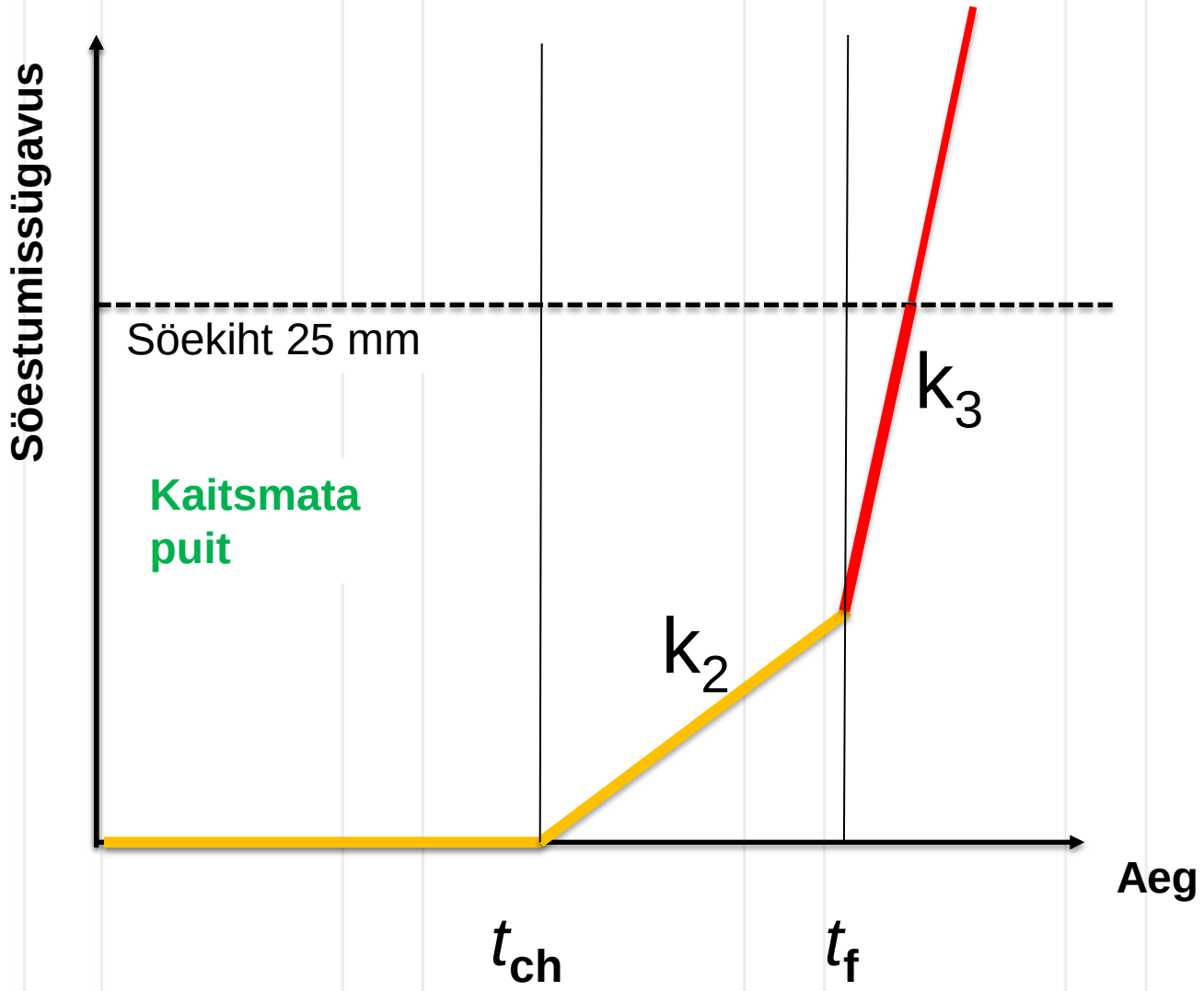
$$d_{char,n} = \beta_n \, t$$

$$\beta_n = k_3 \, k_s \, k_n \, \beta_0$$

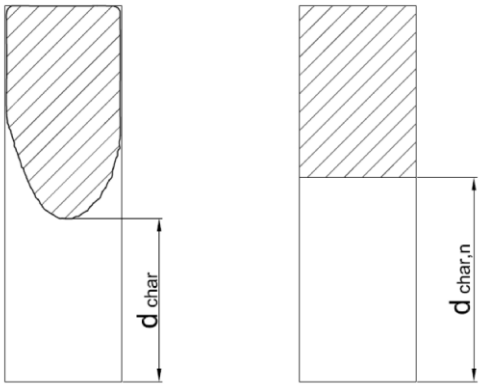
$k_3$ – järelkaitsetegur

Kivivilla jaoks $k_3 = 0{,}036 t_f + 1$

# Puidu söestumine



# Söestumismäär




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

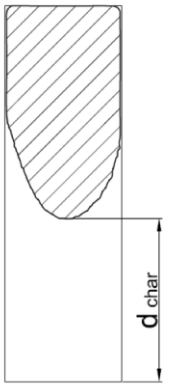
$$\beta_n = k_3 \, k_s \, k_n \, \beta_0$$

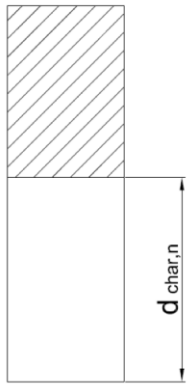
$k_s$ – ristlõiketegur

$$k_s = \beta / \beta_0$$

$\beta$ on määratud 30 mm söestumissügavusel

# Söestumismäär



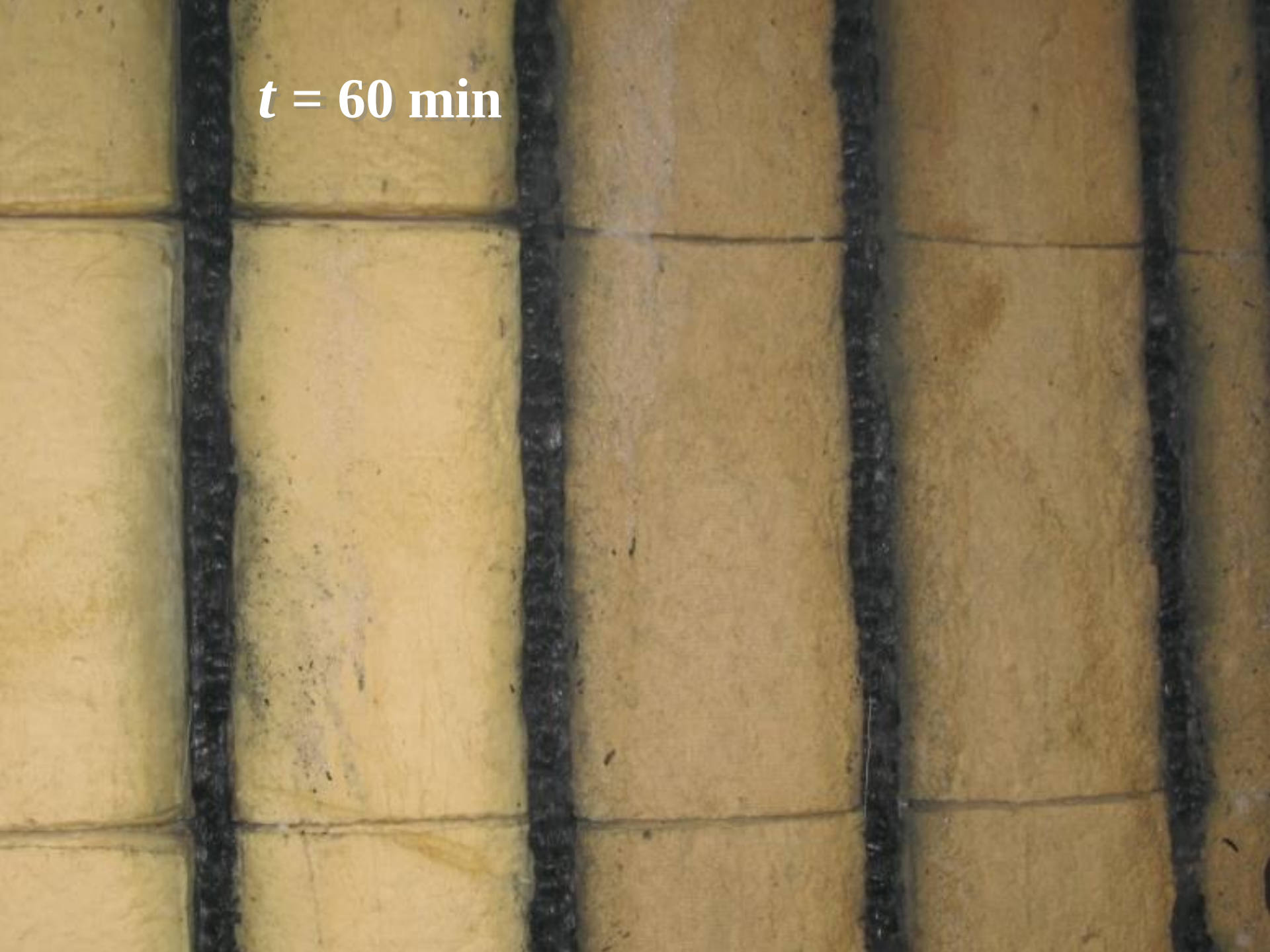




$$d_{char,n} = \beta_n \, t$$

$$\beta_n = k_3 \, k_s \, k_n \, \beta_0$$

$k_n$ – konverteerimistegur

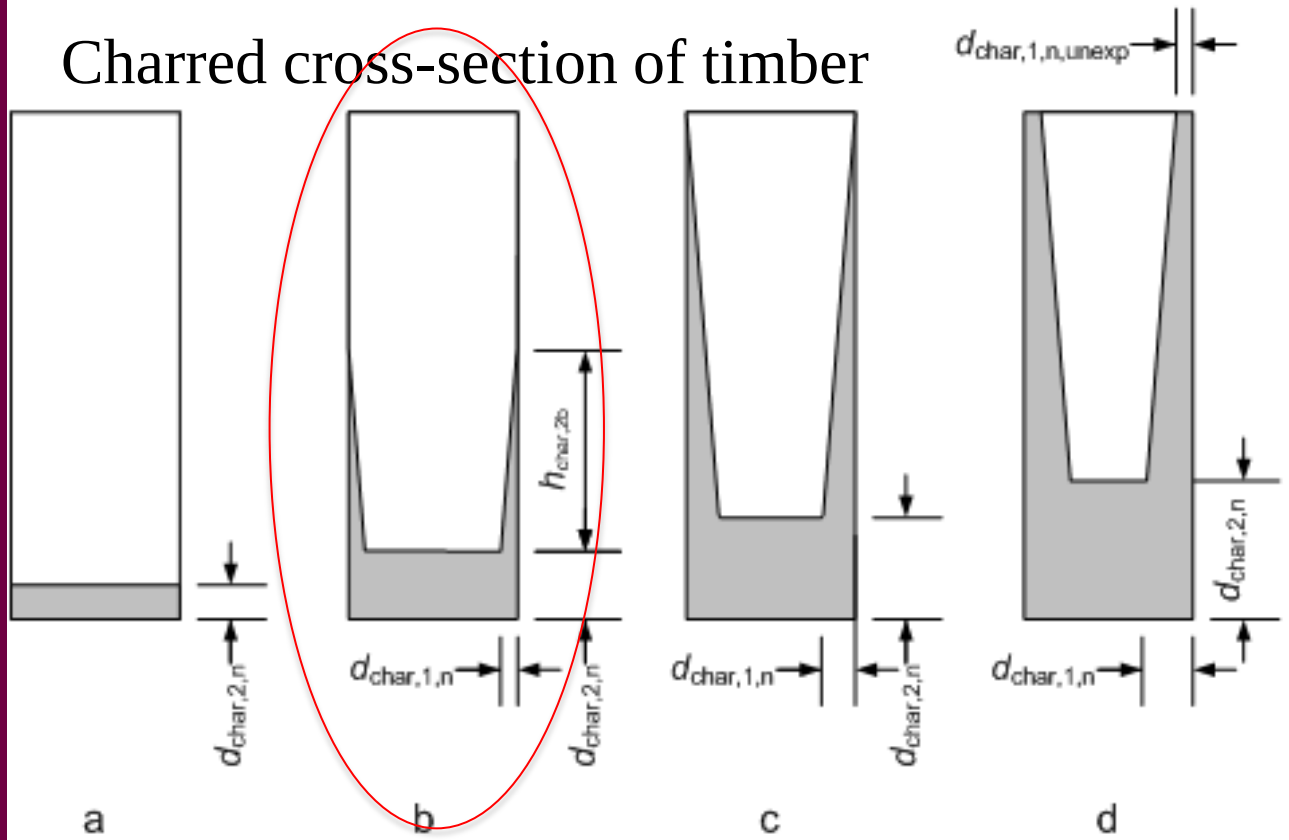
$$k_n = d_{char,n} / d_{char}$$

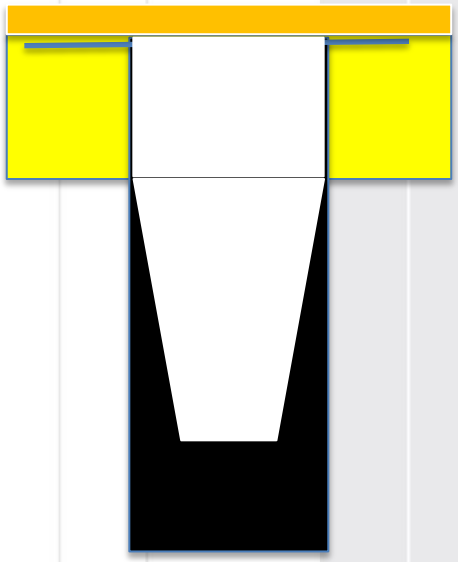

$t$ = 60 min

# Arvutusmudel klaasvillaga

$v_{rec,ins}$=30 mm/min

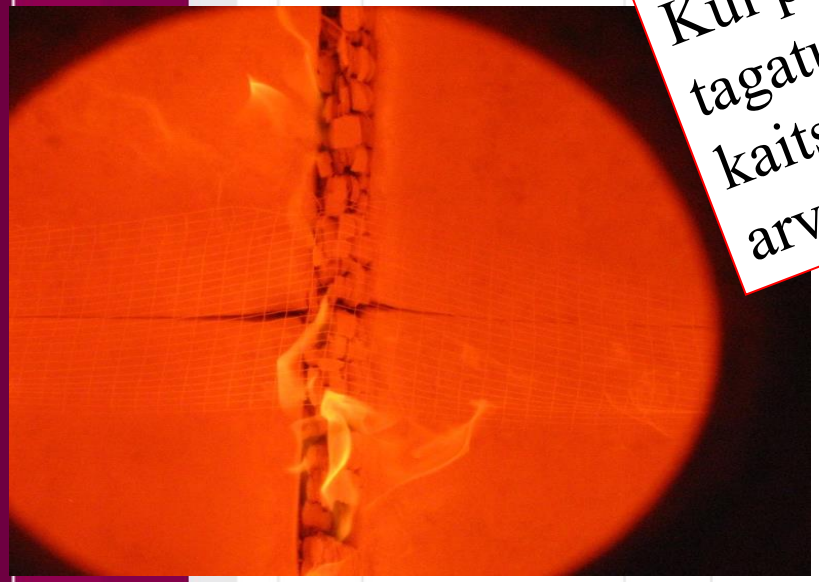
Charred cross-section of timber



# Mineraalvilla kinnitamine

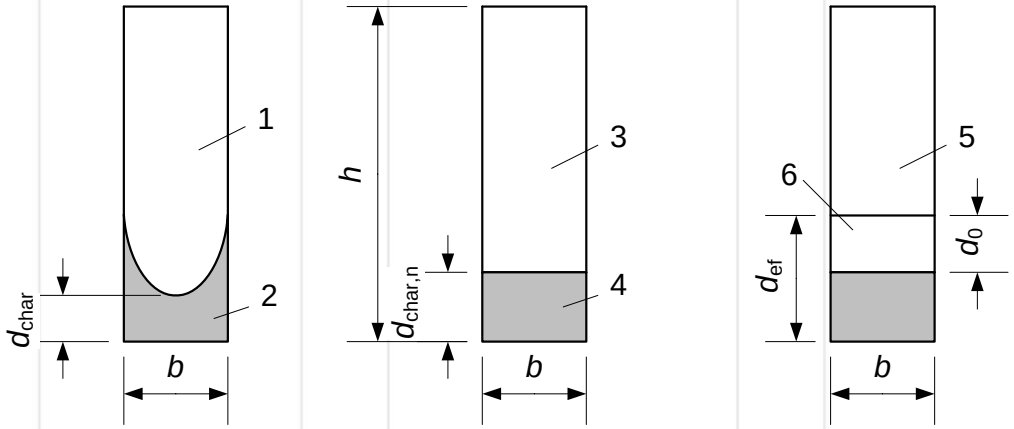
- Ülemõõt
- Liimimine
- Kinnitusvahenditega
- Terasvõrk



Kui pole villa kinnitus tagatud, ei tohi selle kaitsva mõjuga arvestada

# Efektiivristlõikemeetod

Käsiraamatus “Tuleohutud puitmajad”




a) b) c)

$k_{mod,fi} = 1$

1Jääkristlõige
2Söekiht
3Ekvivalentne ristkülikuline ristlõige
4Efektiivne söestumissügavus
5Effektiivristlõige
6Null-tugevusega kiht

# $d_0$

| Tarind | Tulele avatud | Nôtkumine | Limitations | $d_0$ |
|---|---|---|---|---|
| Seinapost | 1 külg | Seinatasandist välja (tugevam suund) | $b \geq 38$ mm<br>$h \geq 95$ mm | 13,5+0,1$h$ |
| Seinapost | 1 külg | Seinatsandis (nôrgem suund) | $b \geq 38$ mm<br>$h \geq 95$ mm | 17+0,25$h$ |
| Seinapost | 2 külge | Seinatasandist välja (tugevam suund) | $b \geq 38$ mm<br>$h = 145$ mm | 25 mm |
| Seinapost | 2 külge | Seinatsandis (nôrgem suund) | $b \geq 38$ mm<br>$h = 145$ mm | 44 mm |

# Söestunud ristlôiked

Söestumine
1 küljest




Söestumine
3 küljest

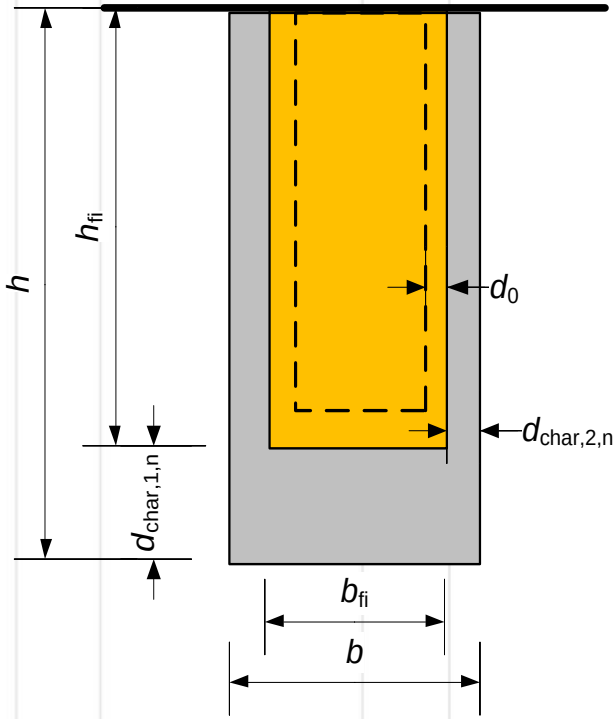


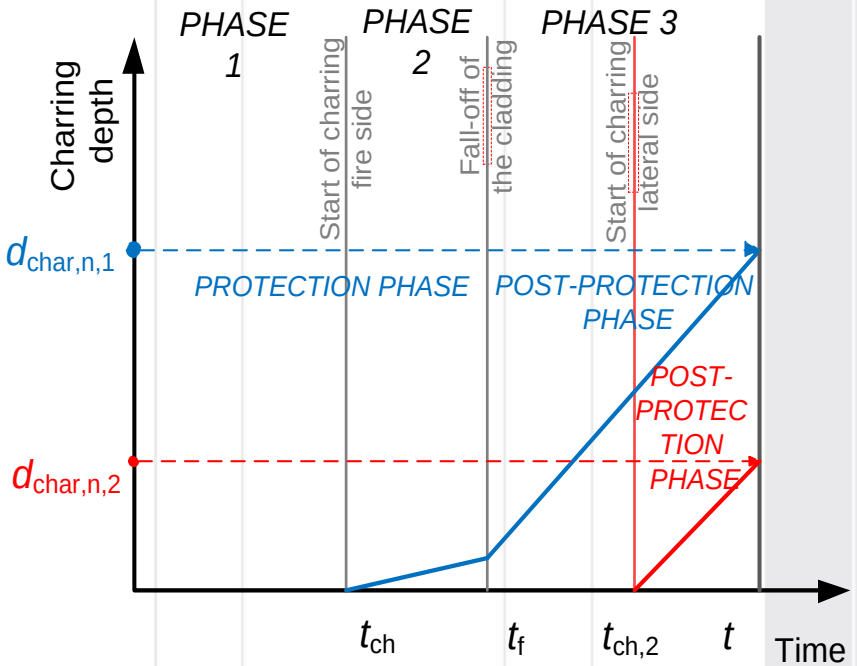


Erinev
söestumine
erinevatel
külgedel



# EN 1995-1-2:2020



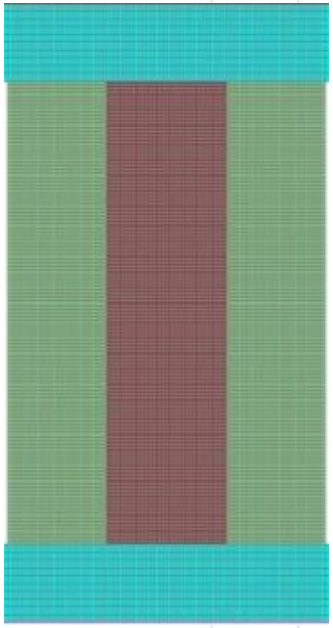

$$d_{\mathrm{char,1,n}} = \beta_0 \cdot k_{\mathrm{s,n}} \cdot k_{\mathrm{pr}} \cdot t \quad \begin{cases} k_{\mathrm{pr}} = k_2 & \text{for} \quad t_{\mathrm{ch,1}} < t < t_{\mathrm{f}} \quad \text{(BOARD)} \\ k_{\mathrm{pr}} = k_3 & \text{for} \quad t > t_{\mathrm{f}} \quad \text{(INS)} \end{cases}$$

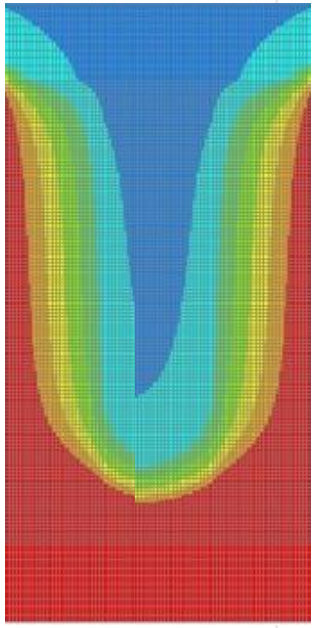
$$d_{\mathrm{char,2,n}} = \beta_0 \cdot k_{\mathrm{pr}} \cdot t \quad \left[ k_{\mathrm{pr}} = k_{3,2} \quad \text{for} \quad t > t_{\mathrm{ch,2}} \right. \quad \text{(INS)}$$

# Termilised simulatsioonid

TERMILISED SIMULATSIOONID

JÄÄKRISTLÕIKED

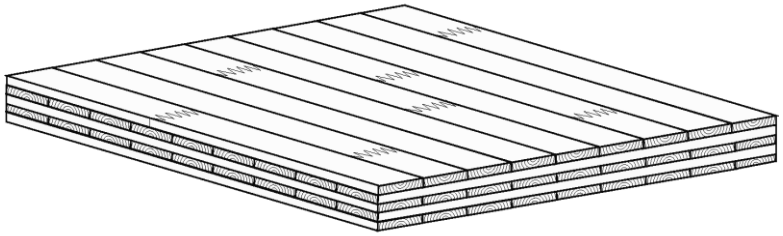




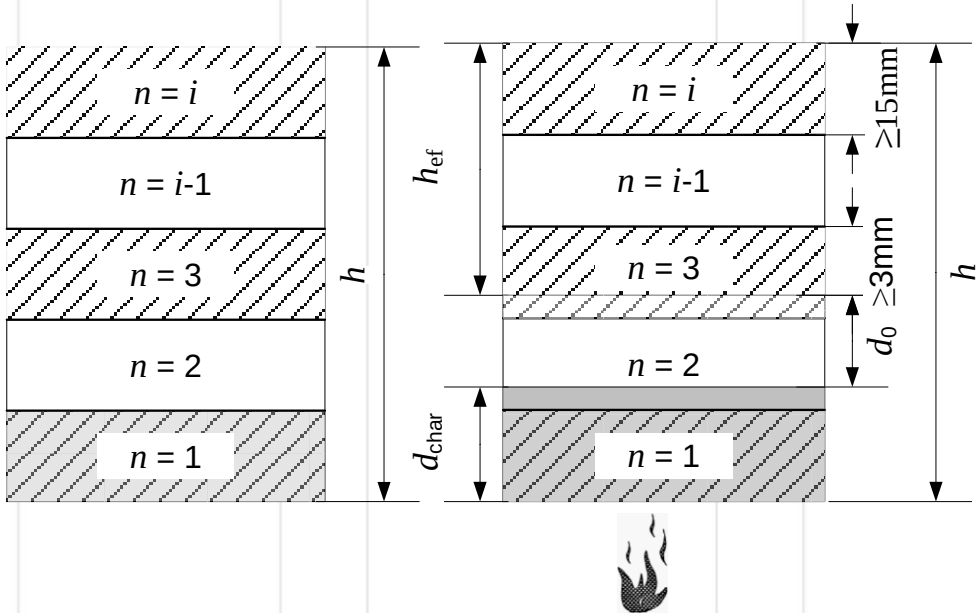
MUDELI DEFINEERIMINE

TEMPERATUURIPROFIIL

# Ristkihtpuit (CLT)



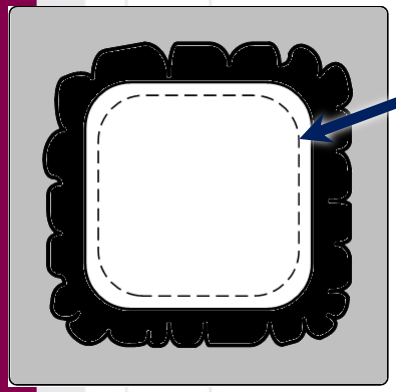
Vähendatud ristlõike meetod:
Lihtsad valemid $d_0$ arvutamiseks

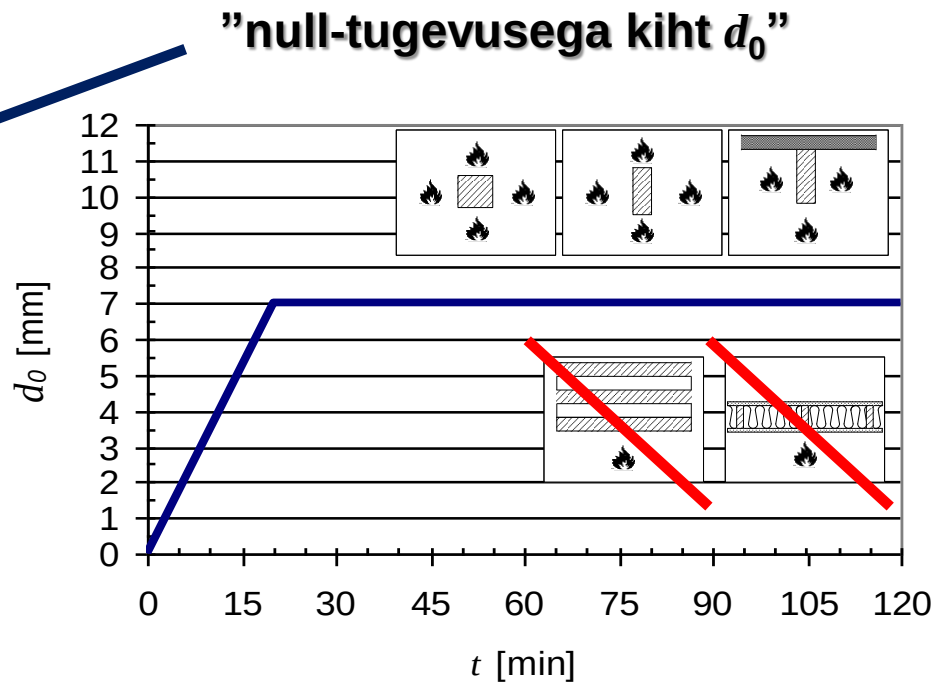


# Ristkihtpuidu arvutusmudel

**Efektiivristlôike arvutusmudel, EN 1995-1-2, 4.2.2:**

- Jääkristlôige ($h_{res}$)
- Efektiivne plaadi paksus? ($h_{ef} = h_{res} - d_0$)





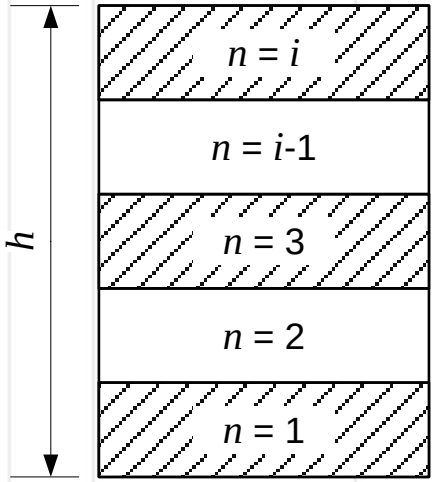
# Ristkihtpuidu arvutusmudel

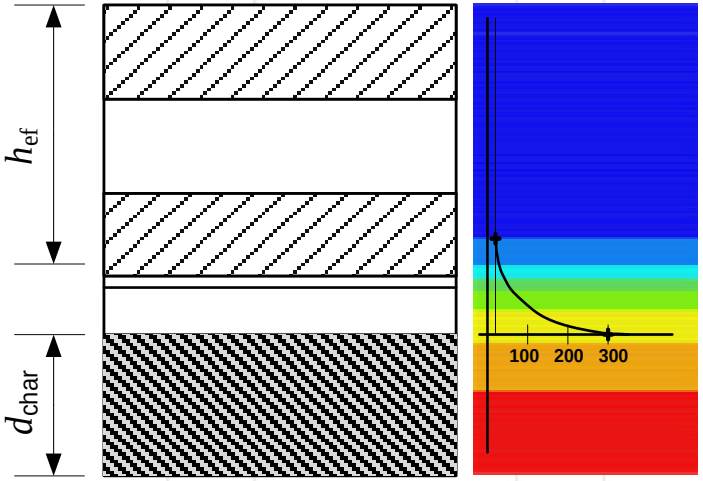
EN 1995-1-2 ei saa kasutada (ebaturvaline)
Söe kihi eemaldumine: liimi ja lamelli suuna mõju

Vähendatud tugevus- ja jäikusomaduste meetodit võib kasutada

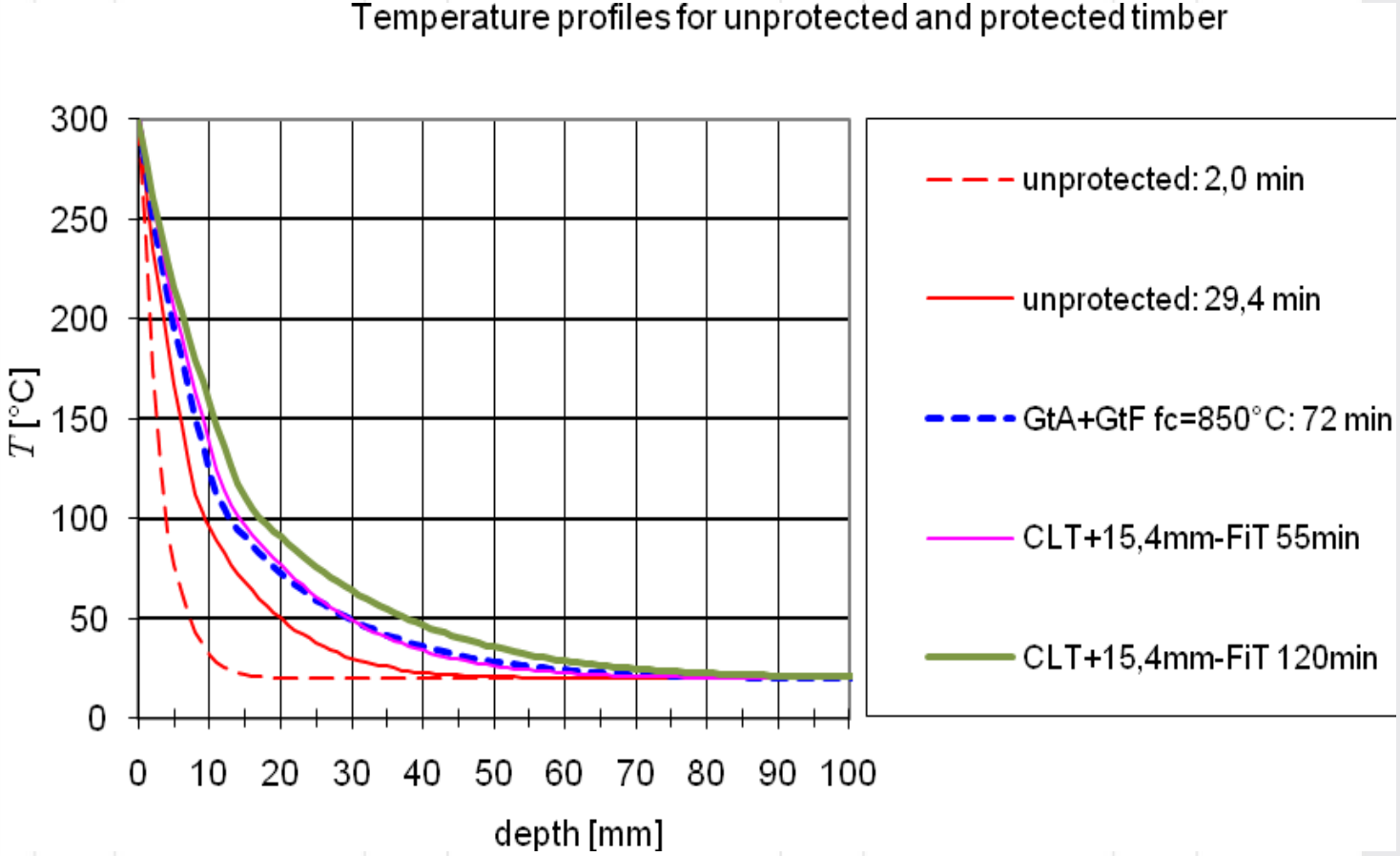
$d_o$=7 mm efektiivristlõikemeetodi jaoks on ebaturvaline

# Simulatsioonid



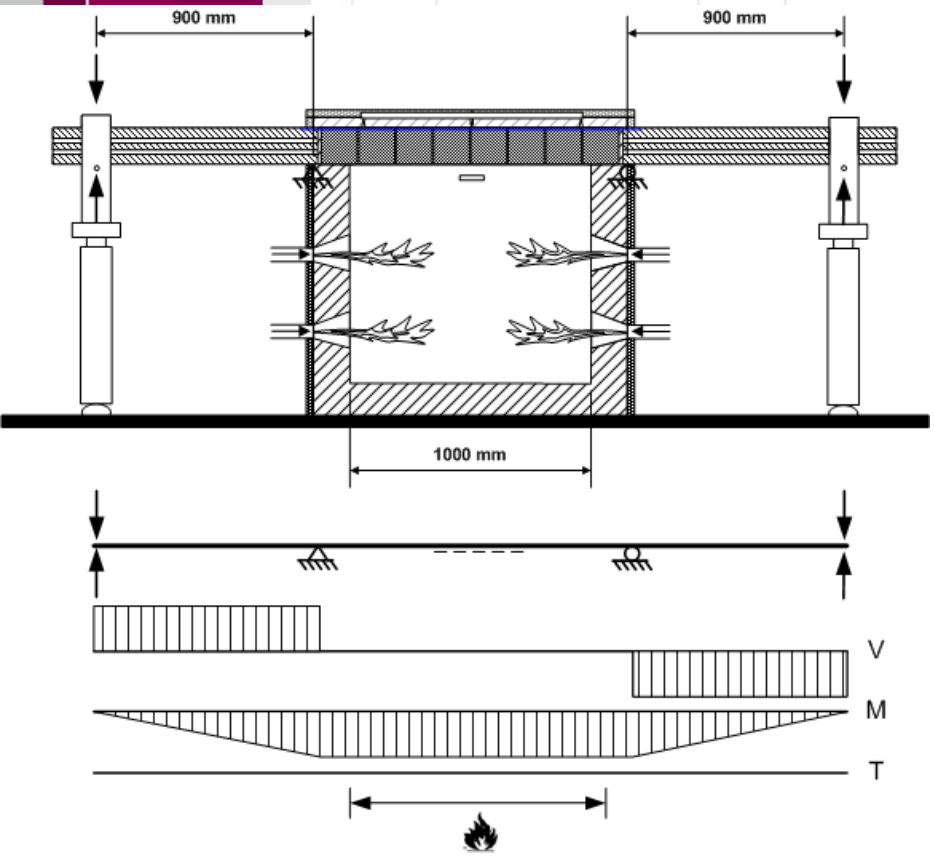



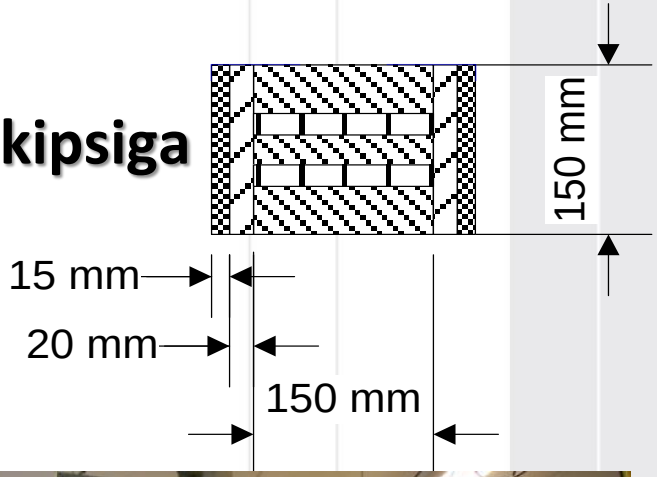
# Temperatuurijaotus ristlôikes



# Tulekatsed

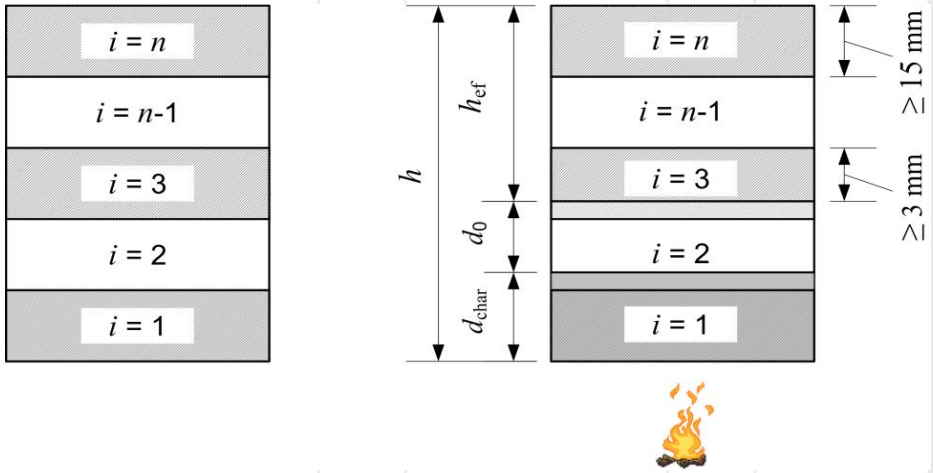
- $w$ = 150 mm
- Küljelt kaetud puidu ja kipsiga




# Ristkihtpuidu arvutusmudel

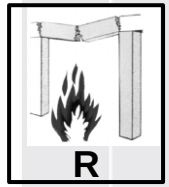
$$d_{ef} = d_{char,0} + k_0 d_0$$

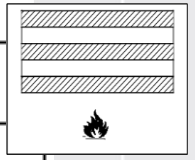



**Näide: $d_0$ viiekihilise RKP jaoks**

| Tulele avatus | Vahelaed | | Seinad | |
|---|---|---|---|---|
| | Kaitsmata | Kaitstud[b] | Kaits-mata | Kaits-tud |
| Tõmbeküljel | $\frac{h}{100} + 10$ | Kui $75\ \text{mm} \leq h \leq 100\ \text{mm}$: $34 - \frac{h}{4}$<br>Kui $h > 100\ \text{mm}$: $\frac{h}{35} + 6$ | Ebaolu-line | Ebaolu-line |
| Surveküljel | $\frac{h}{20} + 11$ | 18 | $\frac{h}{15} + 10,5$ | 20 |

# Ristkihtpuidu arvutusmudel



| 60 min tulele avatus | $d_0$[a] [mm] | | |
|---|---|---|---|
| **CLT-kiht** | **Kaitsmata** | **Kaitstud** Näide: kipsplaadi varisemise aeg $t_f$ = 35 min[b] | **Kaitstud** Näide: kipsplaadi varisemise aeg $t_f \geq 60$ min |
| **45 mm** 15/15/15 | 3,6 | 6,1 | 0,0 |
| **75 mm** 15/15/15/15/15 | 2,4 | 7,2 | 15,0 |
| **105 mm** 15/15/15/15/15/15/15 | 3,5 | 6,5 | 14,4 |
| **60 mm** 20/20/20 | 8,2 | 11,5 | 2,0 |
| **100 mm** 20/20/20/20/20 | 8,2 | 10,7 | 24,2 |
| **120 mm** 20/20/20/20/20/20/20 | 8,6 | 0,0 | 23,9 |
| **75 mm** 25/25/25 | 13,1 | 20,7 | 5,7 |
| **125 mm** 25/25/25/25/25 | 12,0 | 20,5 | 2,9 |
| **175 mm** 25/25/25/25/25/25/25 | 0,0 | 0,0 | 1,9 |

$d_0 \neq 7$ mm

# Tänan kuulamast!

Alar.Just@ttu.ee

TALLINNA
TEHNIKAÜLIKOOL