netpre

Abcic
Associação Brasileira da Construção Industrializada de Concreto

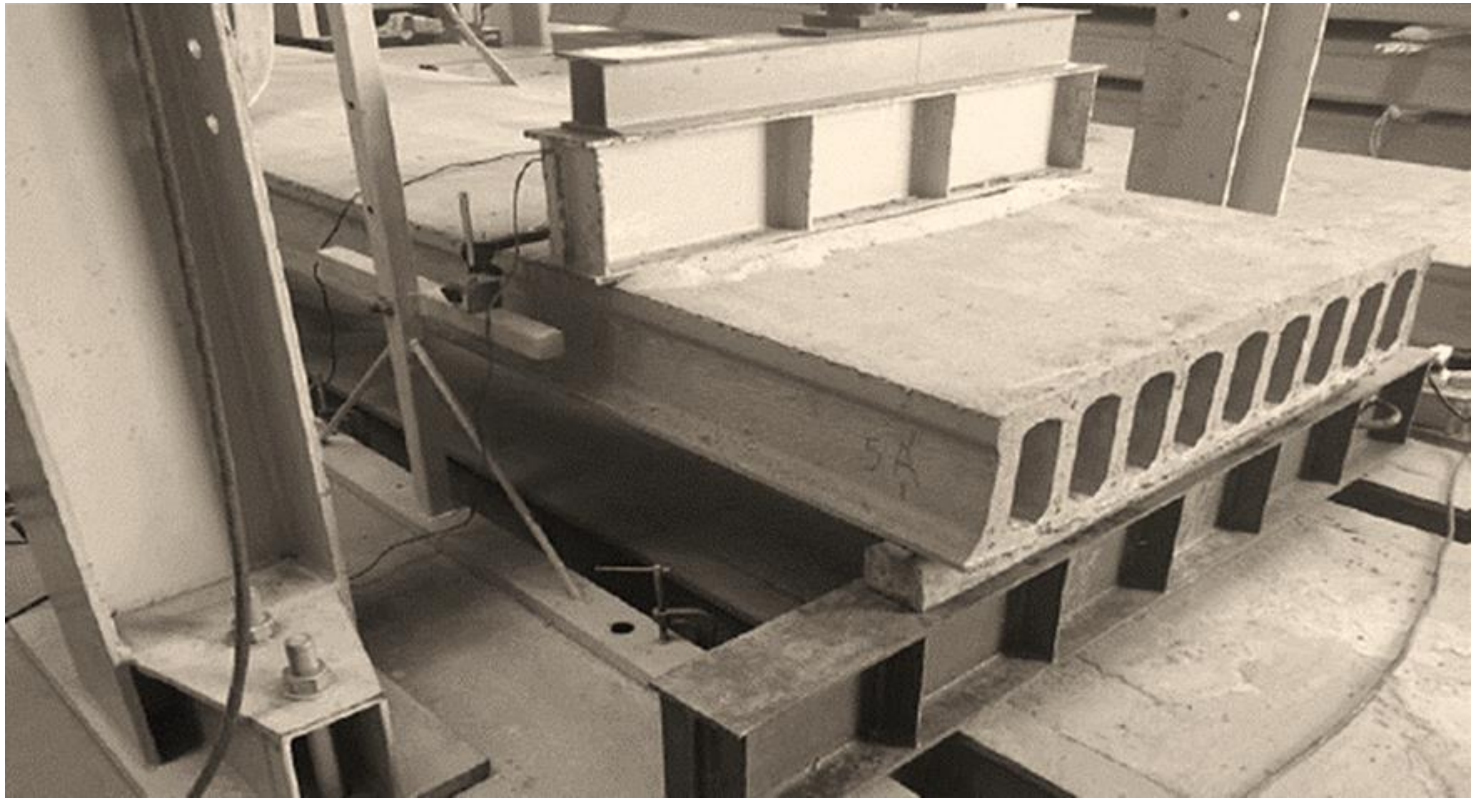
EVENTOS ABCIC
CONCRETESHOW 2017
CURSO E SEMINÁRIO
23 e 24
AGOSTO

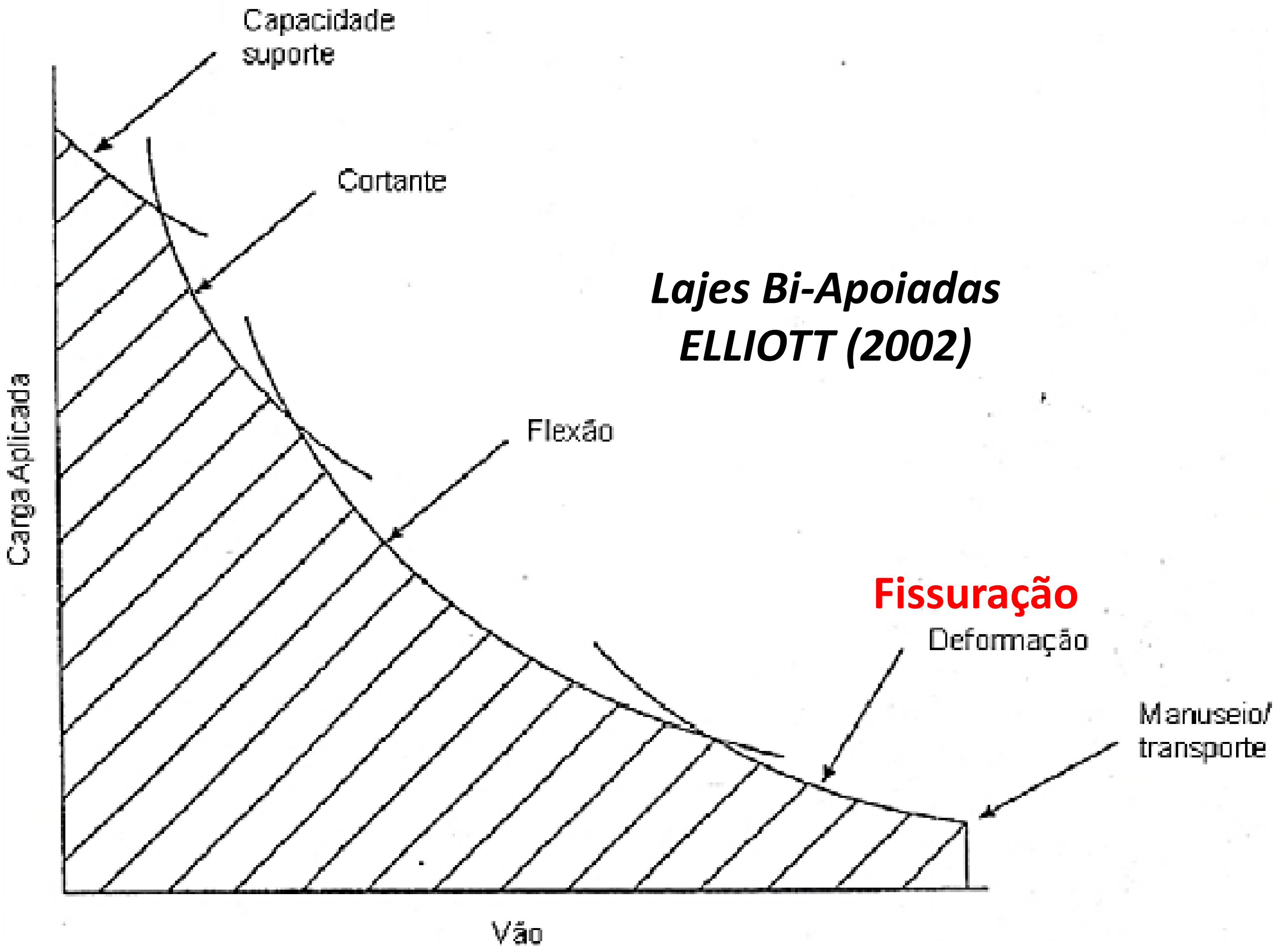
AVANÇOS NA PESQUISA EM LAJES ALVEOLARES PROTENDIDAS: MECANISMOS DE RESISTÊNCIA AO CISALHAMENTO

Marcelo de Araujo Ferreira
Professor Associado – Coordenador NETPRE

ufscar

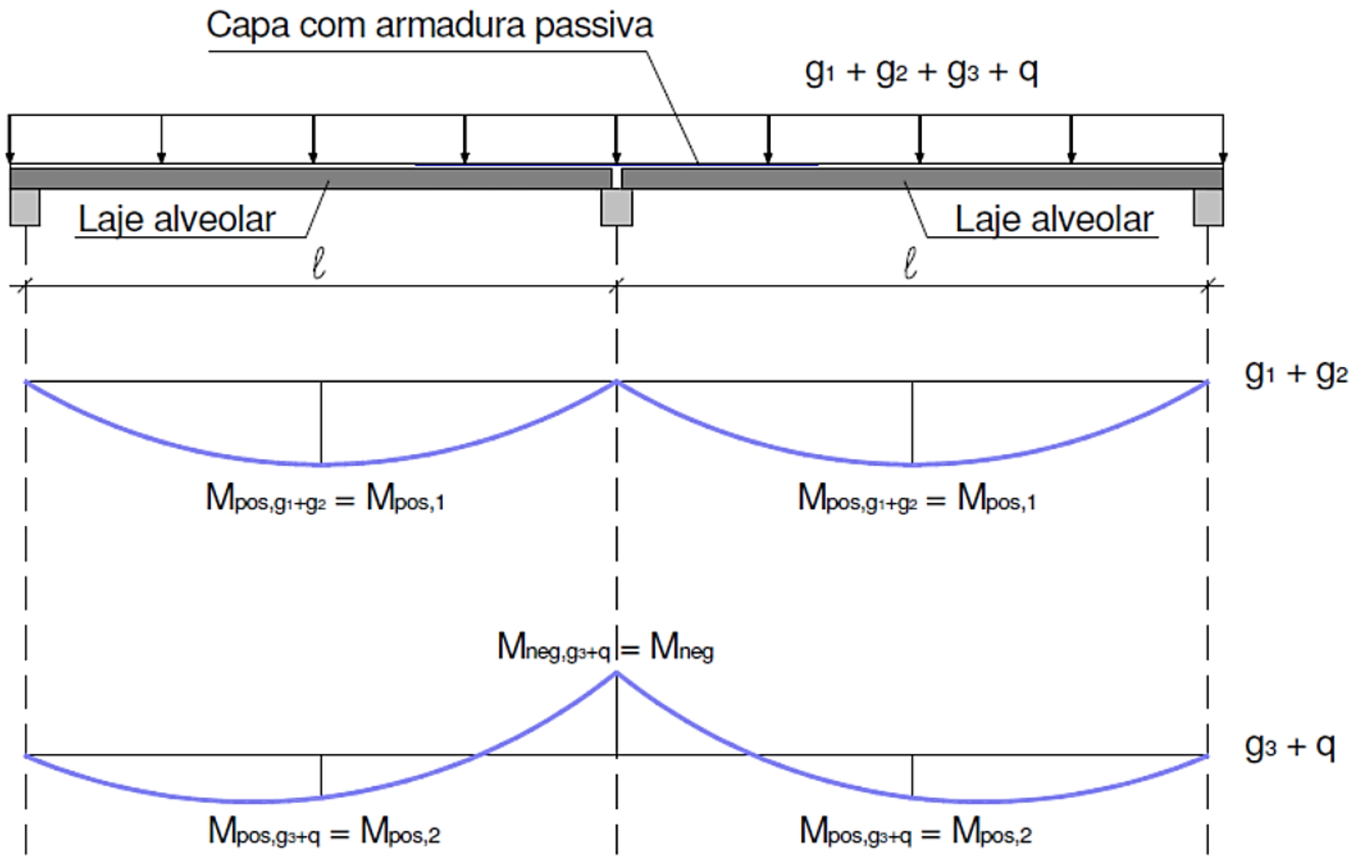
AVANÇOS NA PESQUISA EM LAJES ALVEOLARES PROTENDIDAS: MECANISMOS DE RESISTÊNCIA AO CISALHAMENTO





Lajes Bi-Apoiadas
ELLIOTT (2002)

: Situações críticas variando conforme carga aplicada e vão *(fonte: Elliott, 2002)*.



g_1 = (2,5 a 5 kN)

g_2 = (1,25 a 1,75 kN)

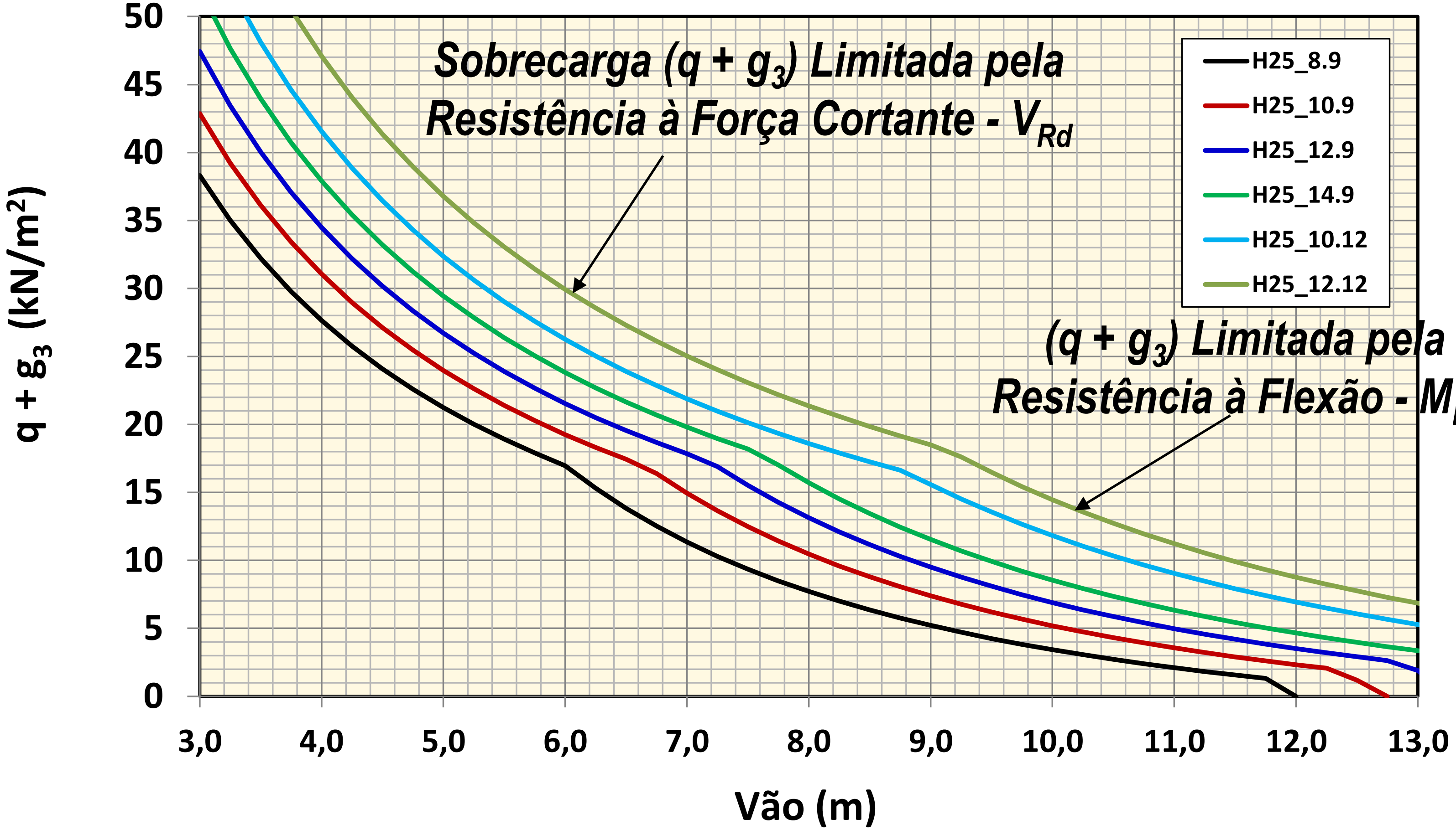
g_3 = (1,0 a 2,5 kN)

g_3 = (3,5 a 50 kN)

Esquemas estruturais com os diagramas de momento fletor das duas fases para dimensionamento de uma laje alveolar com continuidade.

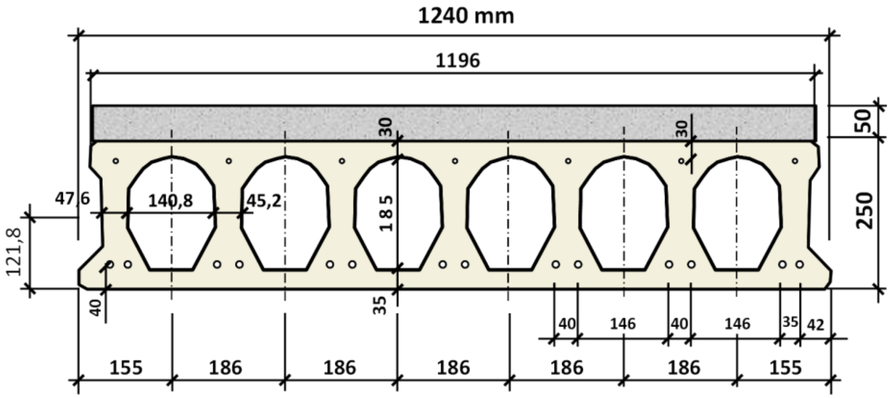
NETPRE-UFSCar – Ferreira, M.A. (2017)

MECANISMOS DE RESISTÊNCIA AO CISALHAMENTO (Situações de Projeto)

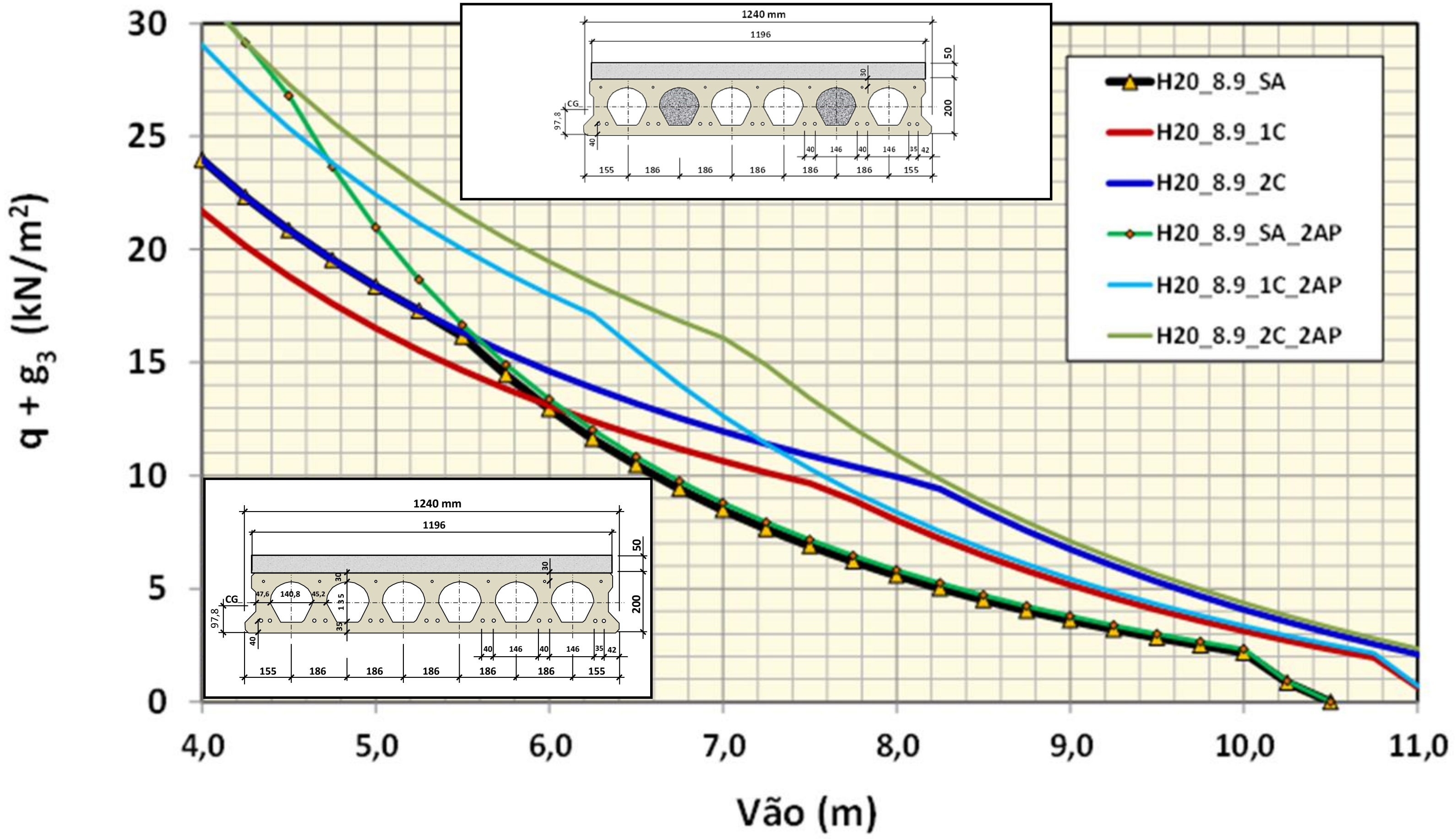


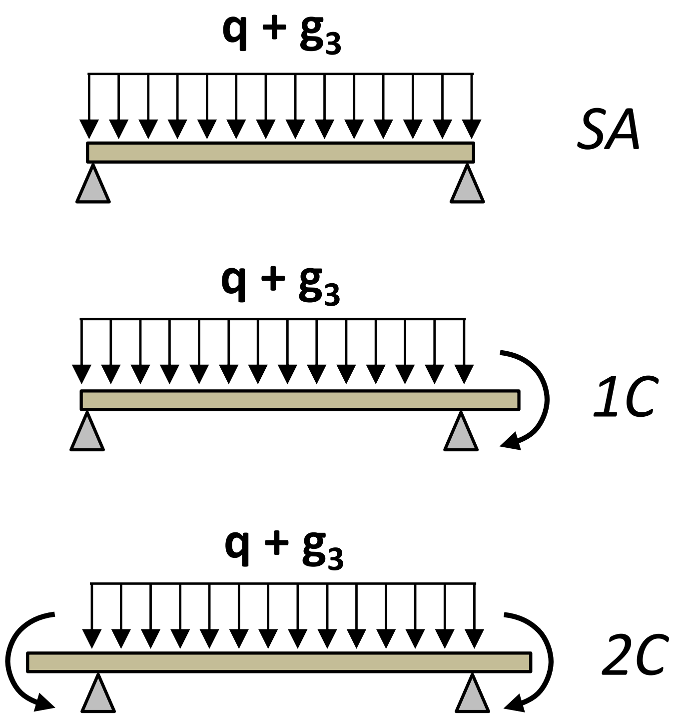
Sobrecarga ($q + g_3$) Limitada pela Resistência à Força Cortante - V_{Rd}

($q + g_3$) Limitada pela Resistência à Flexão - M_{Rd}

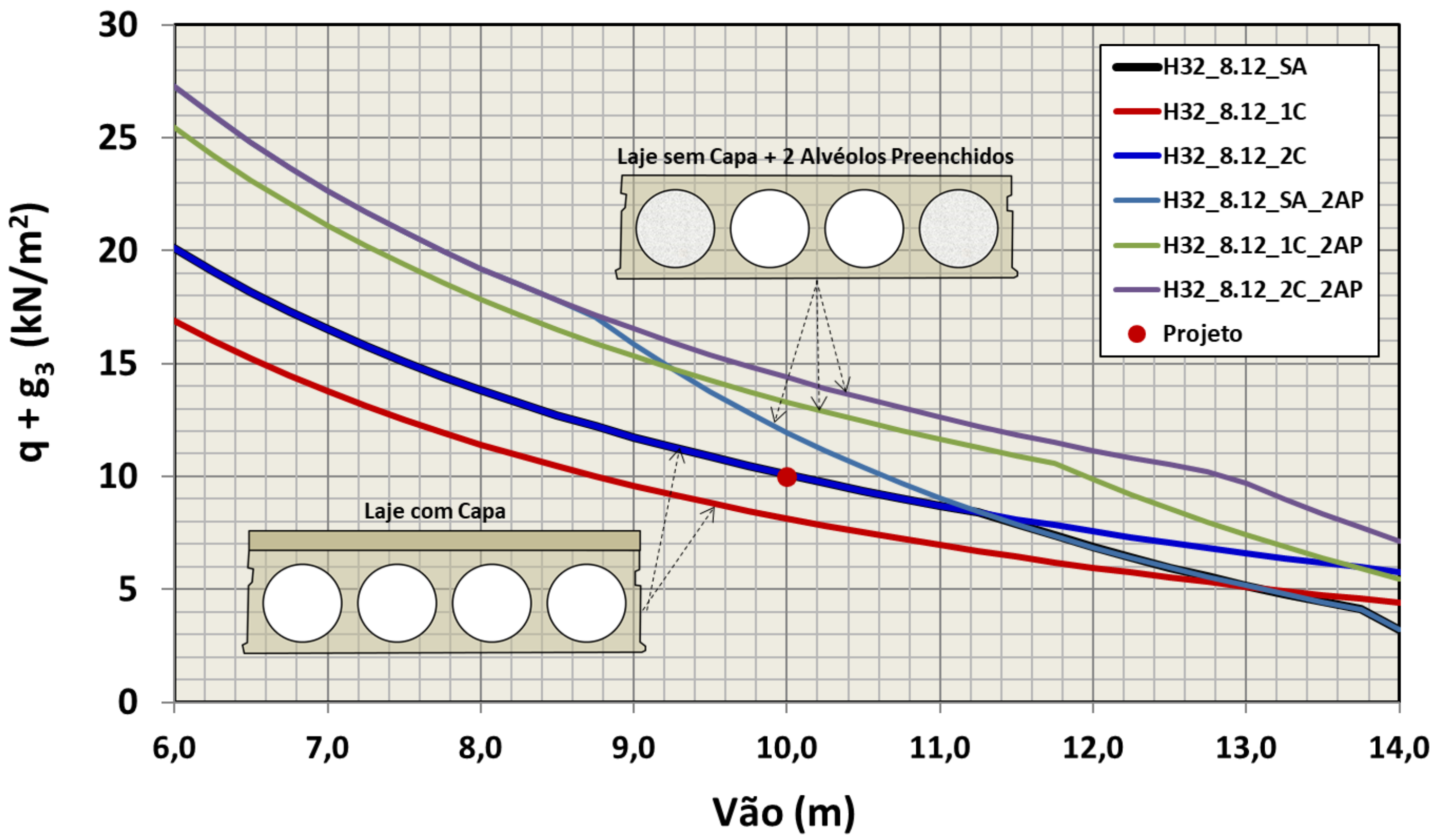


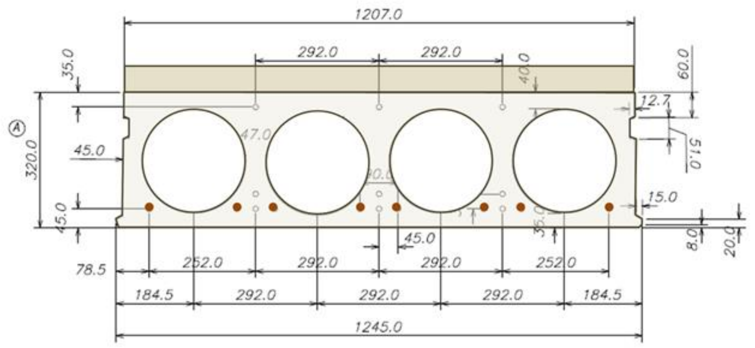
MECANISMOS DE RESISTÊNCIA AO CISALHAMENTO (Situações de Projeto – Continuidade)

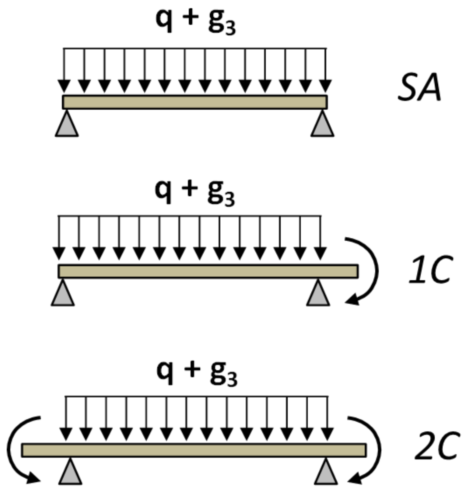




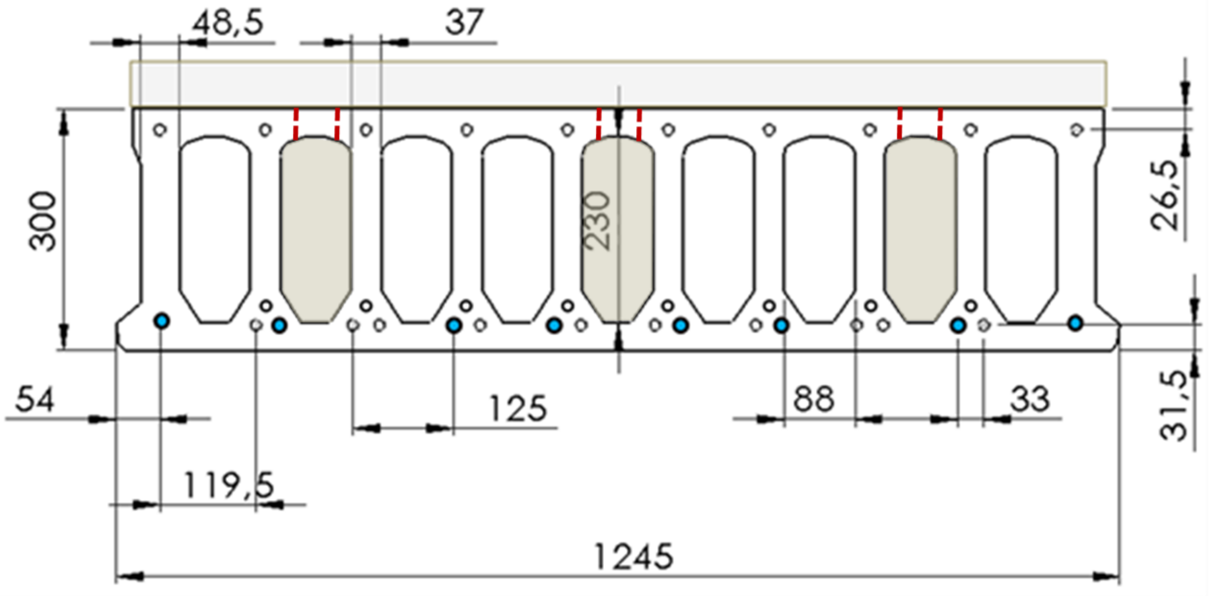
MECANISMOS DE RESISTÊNCIA AO CISALHAMENTO (Preenchimento de Alvéolos)







MECANISMOS DE RESISTÊNCIA AO CISALHAMENTO (Preenchimento de Alvéolos)

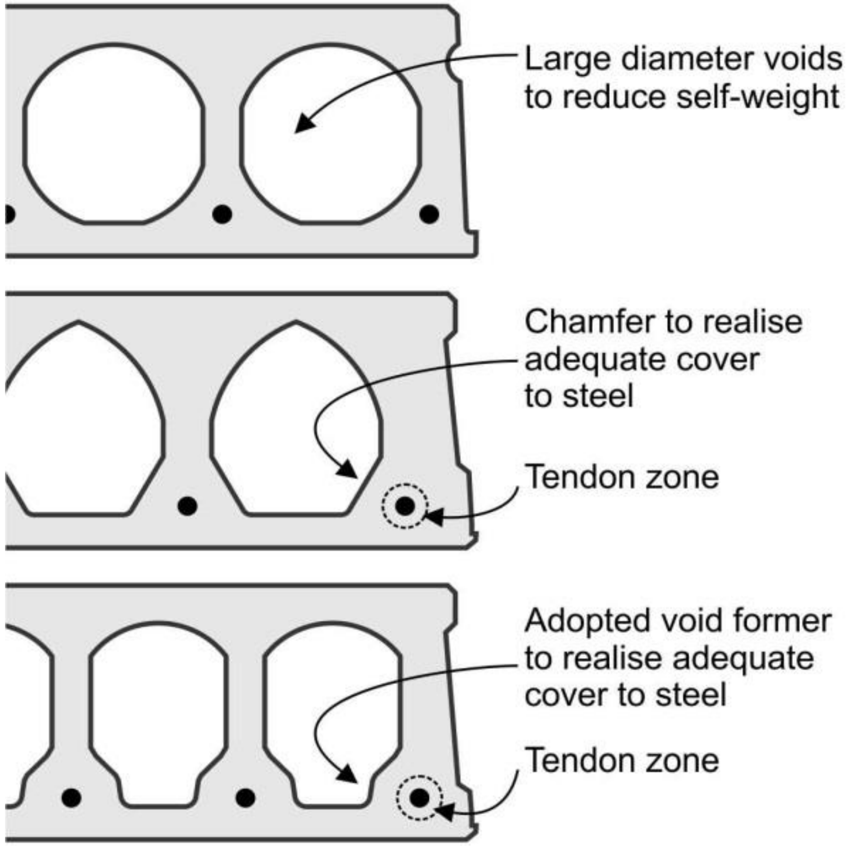


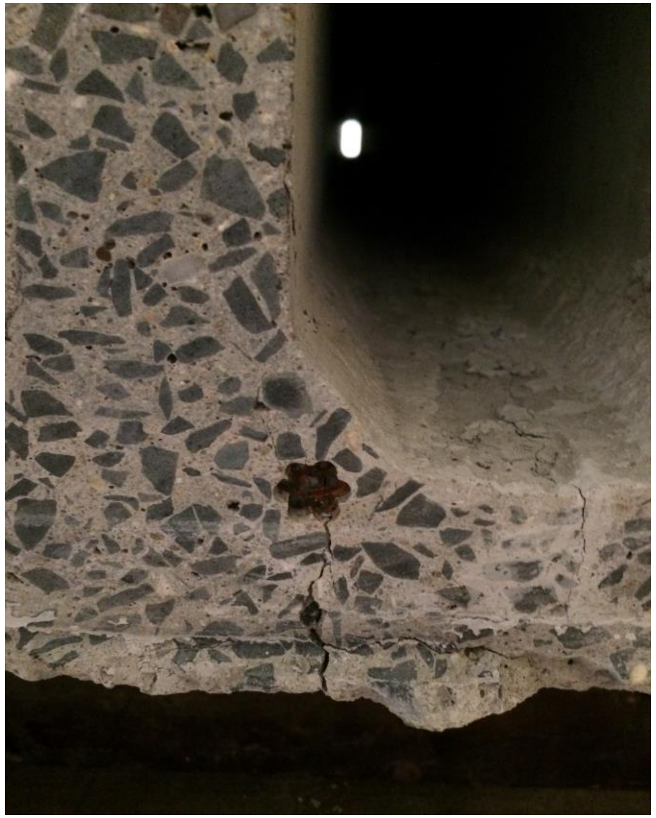
NETPRE-UFSCar – Ferreira, M.A. (2017)

MECANISMOS DE RESISTÊNCIA AO CISALHAMENTO *(Preenchimento de Alvéolos)*

NETPRE-UFSCar – Ferreira, M.A. (2017)

MECANISMOS DE RESISTÊNCIA AO CISALHAMENTO (Efeitos Localizados)





h ≤ 200 mm

Flexure Shear Mechanism

NBR14861:2011

Pesquisas NETPRE 2007-2011

h ≥ 260 mm (300 mm)

Tension Shear Mechanism

EN1168:2005(2009)

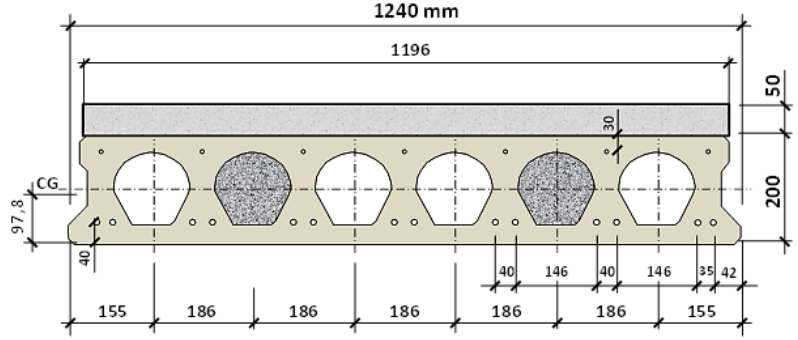
Pesquisas NETPRE 2013-2017

h ≤ 200 mm

Flexure Shear Mechanism

Baixa Eficiência

(NBR14861 - 50%b_{alv})

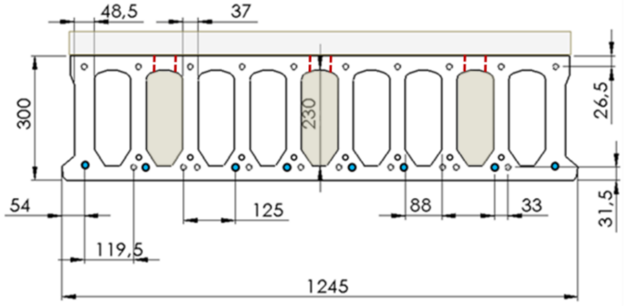


h ≥ 260 mm (300 mm)

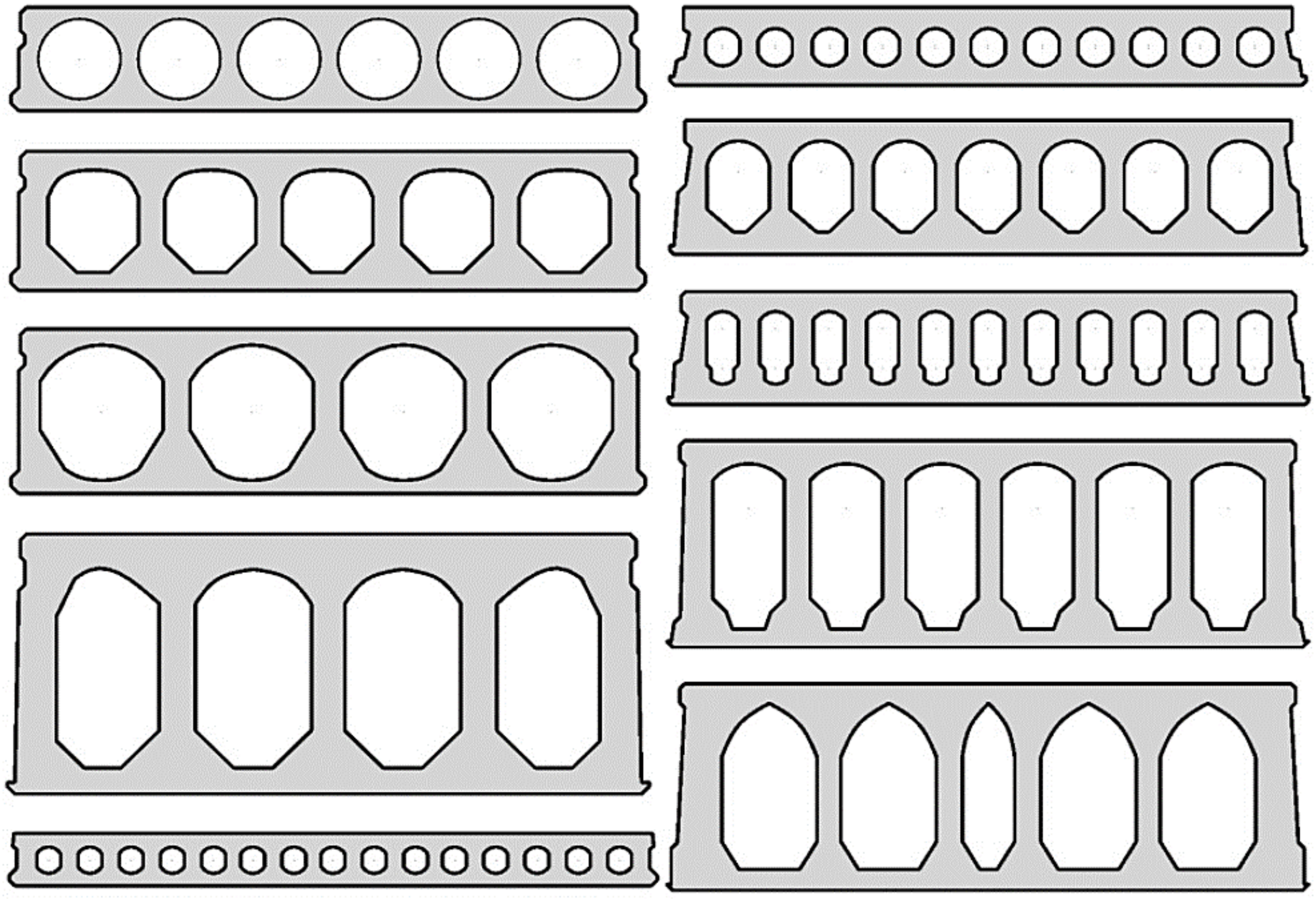
Tension Shear Mechanism

Melhor Eficiência

(FIB & EN1168 – 2/3b_{alv})



MECANISMOS DE RESISTÊNCIA AO CISALHAMENTO EM LAJES ALVEORARES PROTENDIDAS



Alvéolo circular

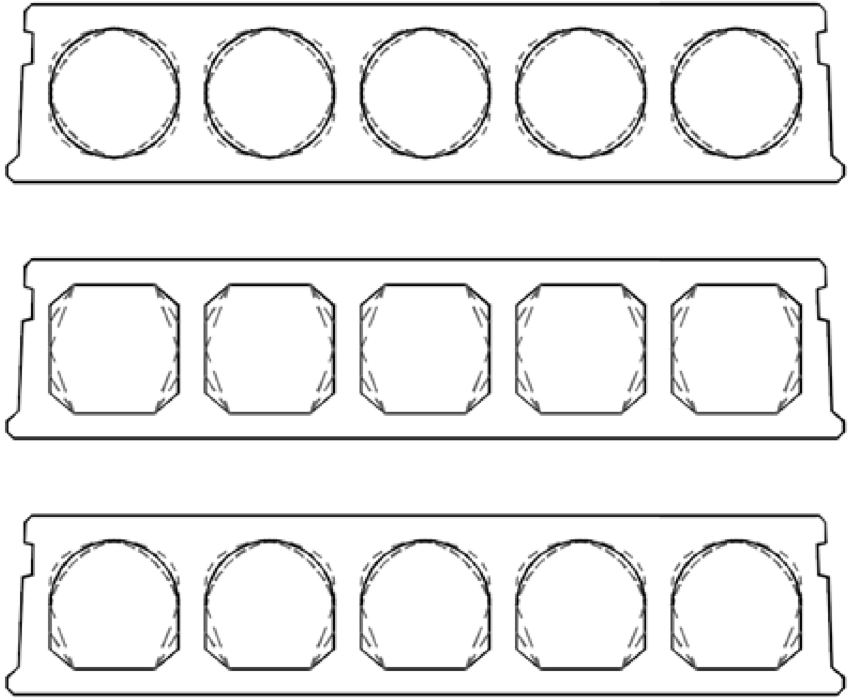
h ≤ 200 mm

Alvéolo oblongo

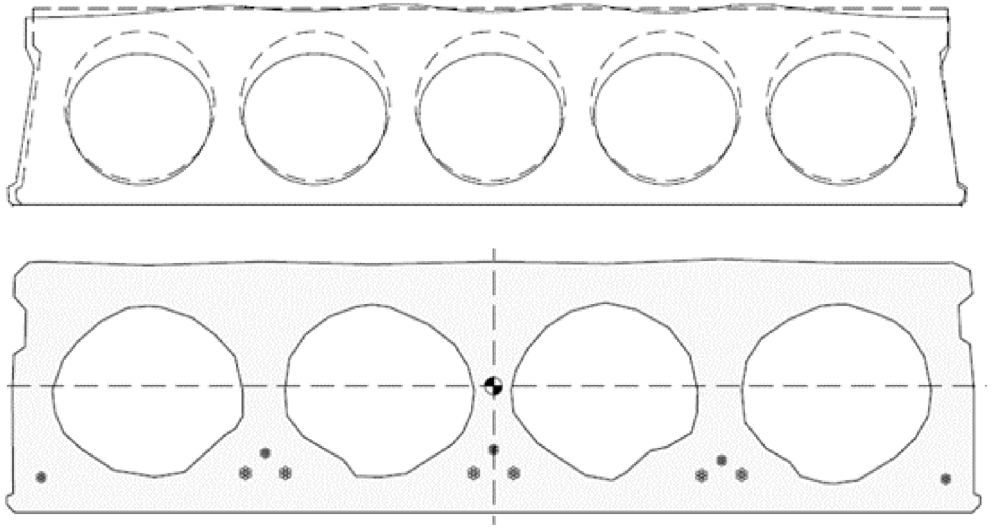
h ≥ 260 mm
(300 mm)

MECANISMOS DE RESISTÊNCIA AO CISALHAMENTO – Geometria dos Alvéolos

Variações das Seções no Projeto



Falta de Conformidade na Produção



❑ NBR14861:2011 (NBR6118:2014) – MECANISMO DE CISALHAMENTO EM REGIÃO FISSURADA

$$V_{Rd1} = V_{c,1} + V_{p,1}$$

$$V_{c,1} = 0{,}25 \cdot f_{ctd} \cdot k \cdot (1{,}2 + 40 \cdot \rho_1) \cdot \sum b_{w,1} \cdot d$$

$$V_{p,1} = \underline{0{,}15} \cdot \sigma_{cp,1} \cdot \sum b_{w,1} \cdot d \qquad \sigma_{cp,1} = \frac{N_p}{A_c} \cdot \xcancel{\alpha} \qquad \alpha = \frac{l_x}{l_{pt2}} \leq 1$$

$$l_{pt} \cong 60\emptyset \qquad l_{p2} \cong 1{,}4 \cdot l_{pt} = 85\emptyset$$

***** A NORMA BRASILEIRA NÃO RECONHECE A PRESENÇA DO MECANISMO DE RUPTURA POR TRAÇÃO DIAGONAL *****

$$V_{Rd,c} = 0{,}25 f_{ctd} k (1{,}2 + 40\rho_1) b_w d + 0{,}15 \sigma_{cp} b_w d \quad (3)$$

The theoretical characteristic shear resistance (calculated with $\gamma_c = 1{,}0$) can be defined by:

$$V_{R,k} = V_{c,k} + V_{p,k} \quad (4)$$

Where:

$$V_{c,k} = 0{,}25 f_{ctk0{,}05} k (1{,}2 + 40\rho_1) b_w d \quad (5)$$

$$\boxed{V_{p,k} = \alpha_l \sigma_{cp} b_w d} \quad (6)$$

According to the EC2 Commentary (2008) *apud* Marquesi (2014), for the load span from the support varying between 2,5d ≤ a ≤ 4d, $V_{p,k}$ is given by:

$$0{,}15 \sigma_{cp} b_w d \leq V_{p,k} \leq 0{,}24 \sigma_{cp} b_w d \quad (7)$$

$\alpha_l = 0{,}15$ is the minimum value for design according to FIB Bulletin 6

Catoia & Ferreira (2017)

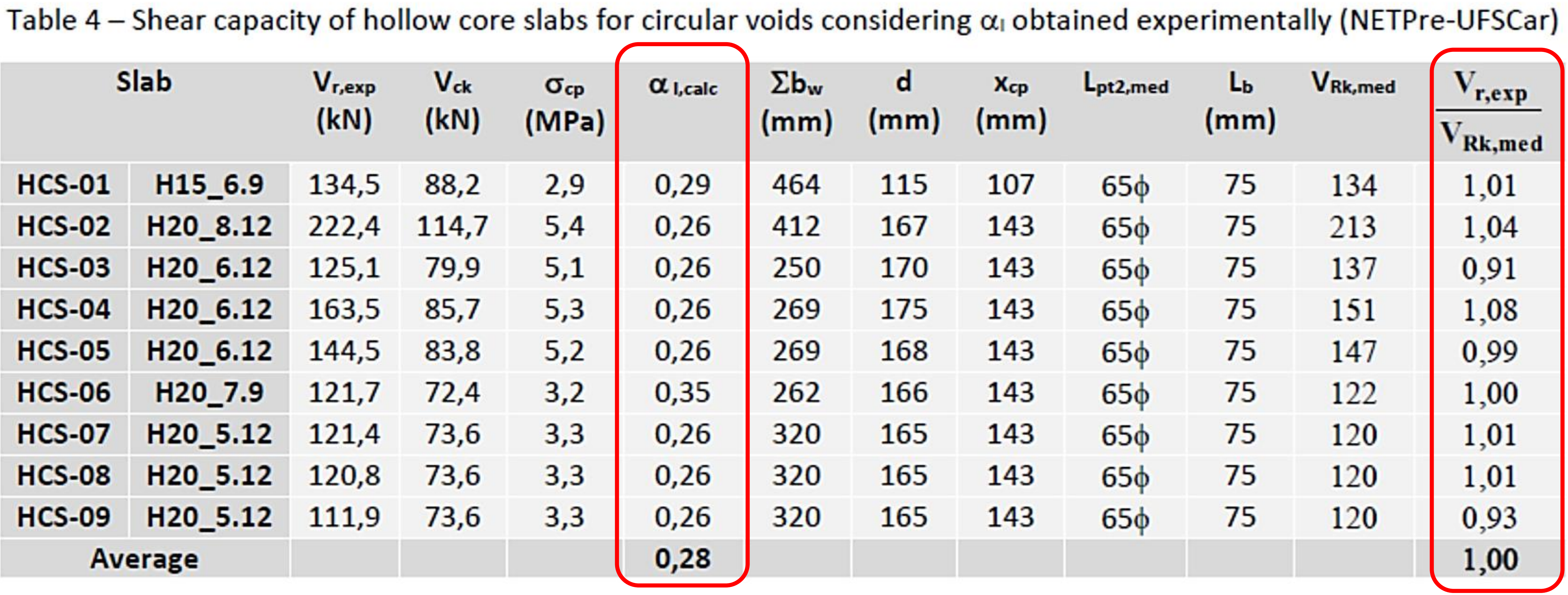


Table 4 – Shear capacity of hollow core slabs for circular voids considering α_l obtained experimentally (NETPre-UFSCar)

Slab		$V_{r,exp}$ (kN)	V_{ck} (kN)	σ_{cp} (MPa)	$\alpha_{l,calc}$	Σb_w (mm)	d (mm)	x_{cp} (mm)	$L_{pt2,med}$	L_b (mm)	$V_{Rk,med}$	$\frac{V_{r,exp}}{V_{Rk,med}}$
HCS-01	H15_6.9	134,5	88,2	2,9	0,29	464	115	107	65ϕ	75	134	1,01
HCS-02	H20_8.12	222,4	114,7	5,4	0,26	412	167	143	65ϕ	75	213	1,04
HCS-03	H20_6.12	125,1	79,9	5,1	0,26	250	170	143	65ϕ	75	137	0,91
HCS-04	H20_6.12	163,5	85,7	5,3	0,26	269	175	143	65ϕ	75	151	1,08
HCS-05	H20_6.12	144,5	83,8	5,2	0,26	269	168	143	65ϕ	75	147	0,99
HCS-06	H20_7.9	121,7	72,4	3,2	0,35	262	166	143	65ϕ	75	122	1,00
HCS-07	H20_5.12	121,4	73,6	3,3	0,26	320	165	143	65ϕ	75	120	1,01
HCS-08	H20_5.12	120,8	73,6	3,3	0,26	320	165	143	65ϕ	75	120	1,01
HCS-09	H20_5.12	111,9	73,6	3,3	0,26	320	165	143	65ϕ	75	120	0,93
Average					**0,28**							**1,00**

Comprimento de Transmissão (Dedução de Ensaios)

Coeficiente de tensão parcial de protensão

$$\alpha_l = \frac{L_x}{L_{pt2}} = \frac{L_x}{1{,}2L_{pt}}$$

Para alvéolos circulares

$$L_x = L_b + \frac{0{,}5h}{0{,}7} = L_b + \frac{h_{cp}}{0{,}7}$$

Onde:

L_x : *Distância entre a borda do apoio até a projeção da interseção do ponto crítico na linha de ruptura com 35º.*

L_b: *Comprimento de apoio*

$$L_{pt2} = 1{,}2\beta\emptyset$$

Catoia & Ferreira (2017)

Table 4 – Shear capacity of hollow core slabs for circular voids considering α_l obtained experimentally (NETPre-UFSCar)

Slab		$V_{r,exp}$ (kN)	V_{ck} (kN)	σ_{cp} (MPa)	$\alpha_{l,calc}$	Σb_w (mm)	d (mm)	x_{cp} (mm)	$L_{pt2,med}$	L_b (mm)	$V_{Rk,med}$	$\frac{V_{r,exp}}{V_{Rk,med}}$
HCS-01	**H15_6.9**	134,5	88,2	2,9	0,29	464	115	107	65ϕ	75	134	1,01
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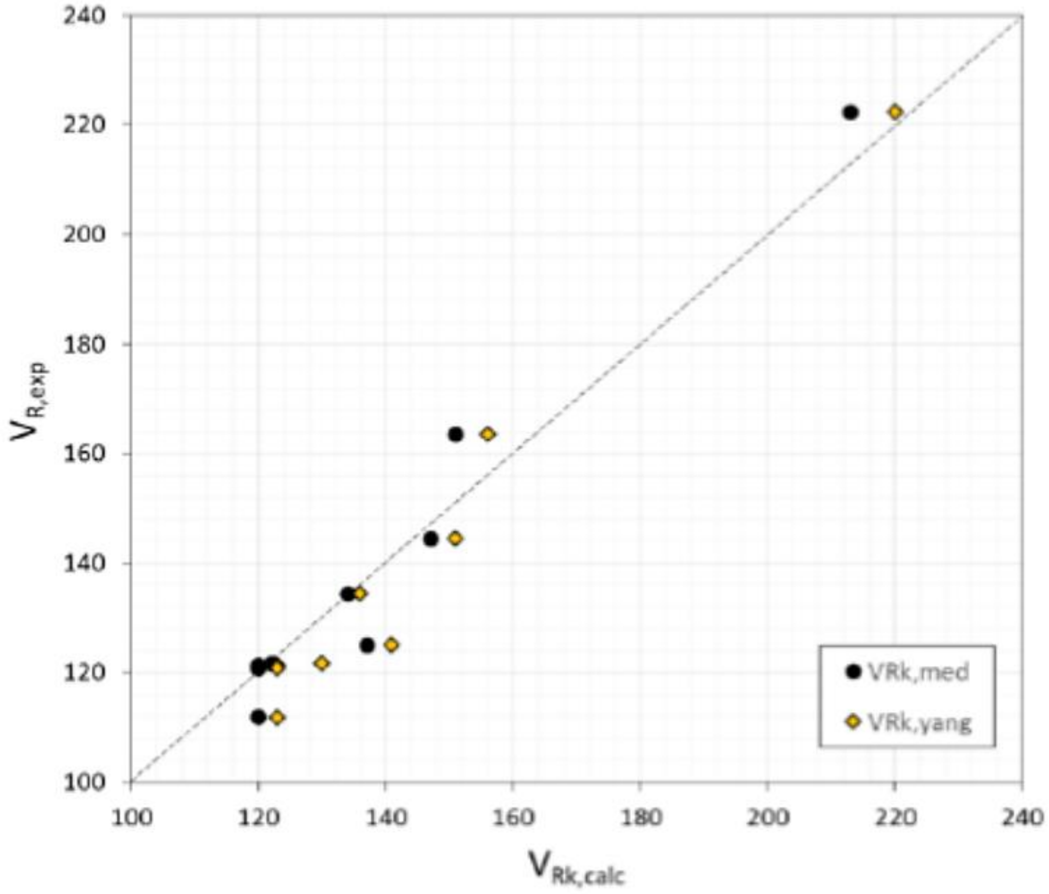
HCS-06	**H20_7.9**	121,7	72,4	3,2	0,35	262	166	143	65ϕ	75	122	1,00
HCS-07	**H20_5.12**	121,4	73,6	3,3	0,26	320	165	143	65ϕ	75	120	1,01
HCS-08	**H20_5.12**	120,8	73,6	3,3	0,26	320	165	143	65ϕ	75	120	1,01
HCS-09	**H20_5.12**	111,9	73,6	3,3	0,26	320	165	143	65ϕ	75	120	0,93
Average					**0,28**							**1,00**

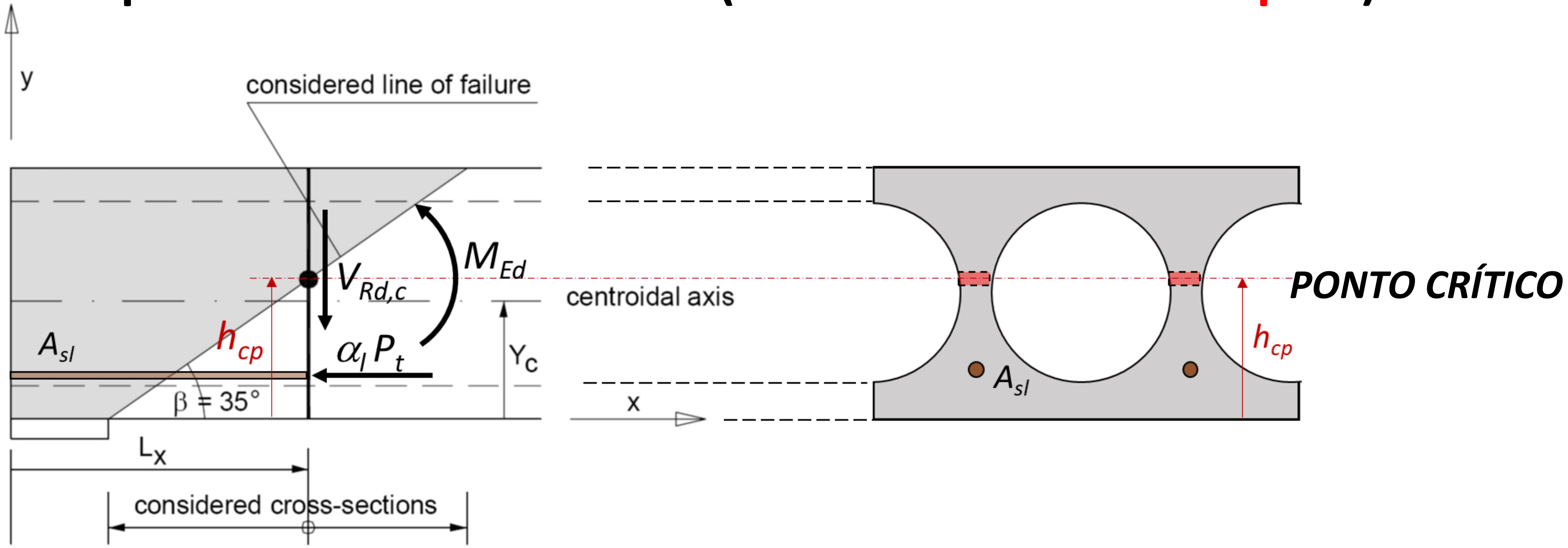

Flexure Shear Capacity

$$V_{Rd,c} = 0{,}25 f_{ctd} k(1{,}2 + 40\rho_1) b_w d + \boxed{0{,}15} \sigma_{cp} b_w d$$

0,25

Catoia & Ferreira (2017)

Comprimento de Transmissão (Protensão Parcial no Apoio)

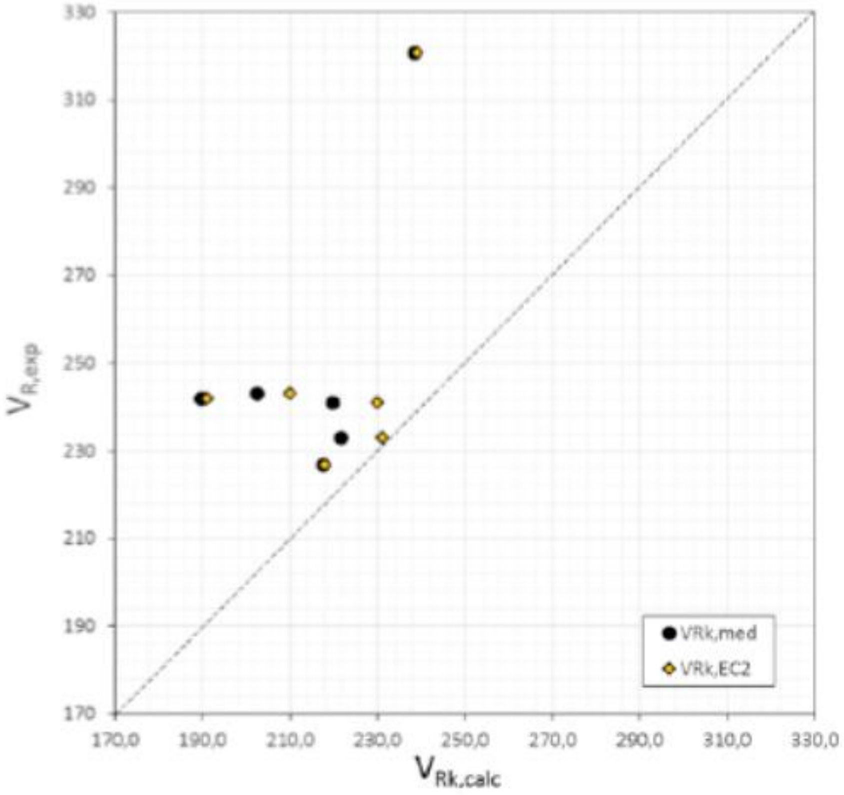


$$\alpha_l = L_x / L_{pt2} = L_x / (1{,}2 L_{pt1}) = L_x / (1{,}2\beta\phi)$$

L_x – is the distance of the considered point on the line of failure from the starting point of the transmission length (= x)

Reference: PROPOSAL FOR AMENDMENT 3 CEN/TC229/WG1/N. 650bis
EN 1168:2005 Precast concrete products – Hollow core slabs

Tension Shear Capacity

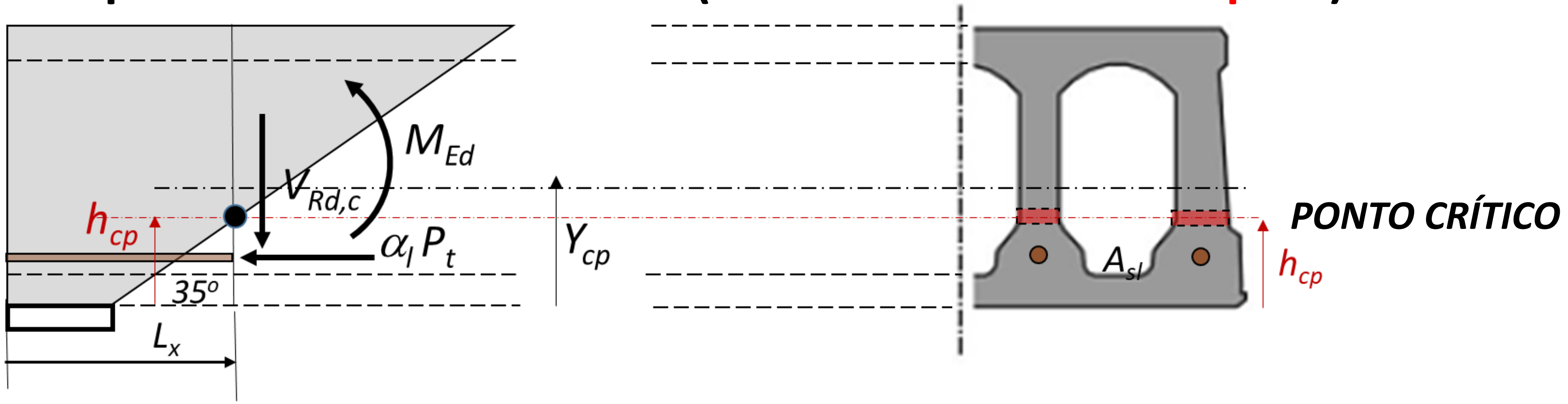


$$V_{Rd,c} = \frac{I.b_w}{S}.\sqrt{(f_{ctd})^2 + \alpha_1.\sigma_{cp}.f_{ctd}}$$

α_1 : L_x/L_{pt2}

Catoia & Ferreira (2017)

Comprimento de Transmissão (Protensão Parcial no Apoio)



$$L_x = L_b + (h_{cp} / 0{,}7)$$

$$\alpha_l = L_x / L_{pt2} = L_x / (1{,}2L_{pt1}) = L_x / (1{,}2\beta\phi)$$

L_x – is the distance of the considered point on the line of failure from the starting point of the transmission length (= x)

Reference: PROPOSAL FOR AMENDMENT 3 CEN/TC229/WG1/N. 650bis
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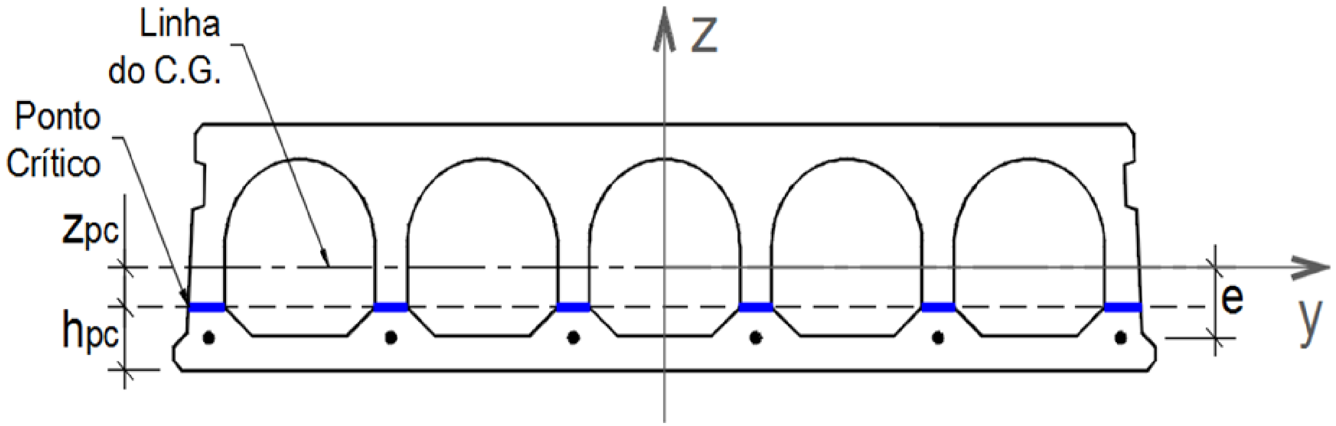
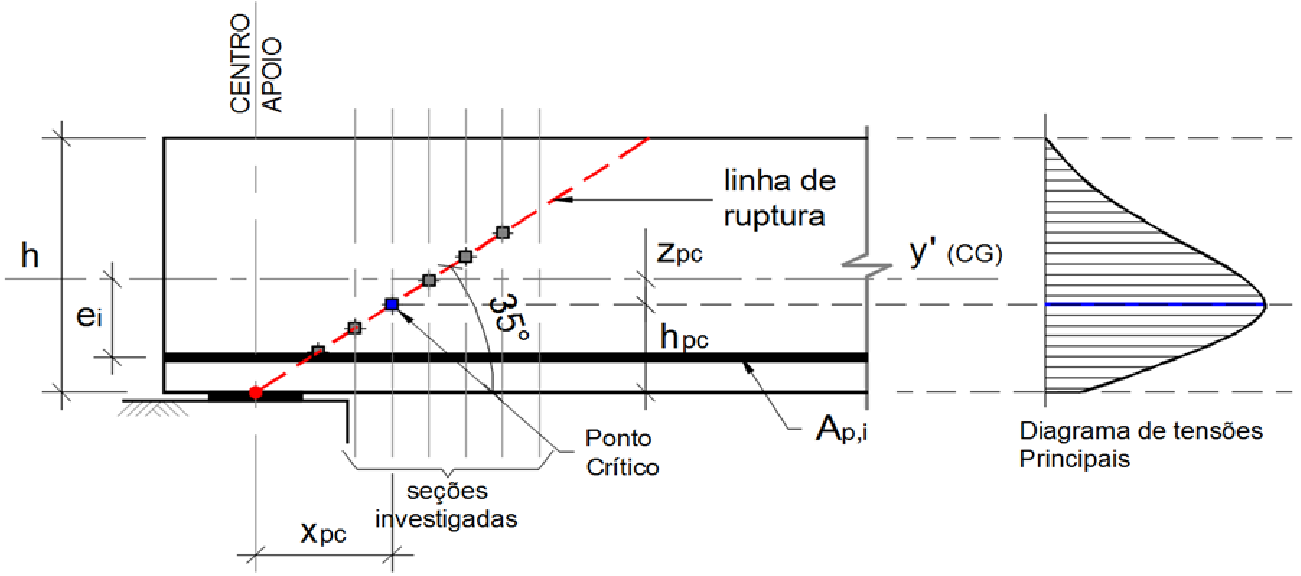
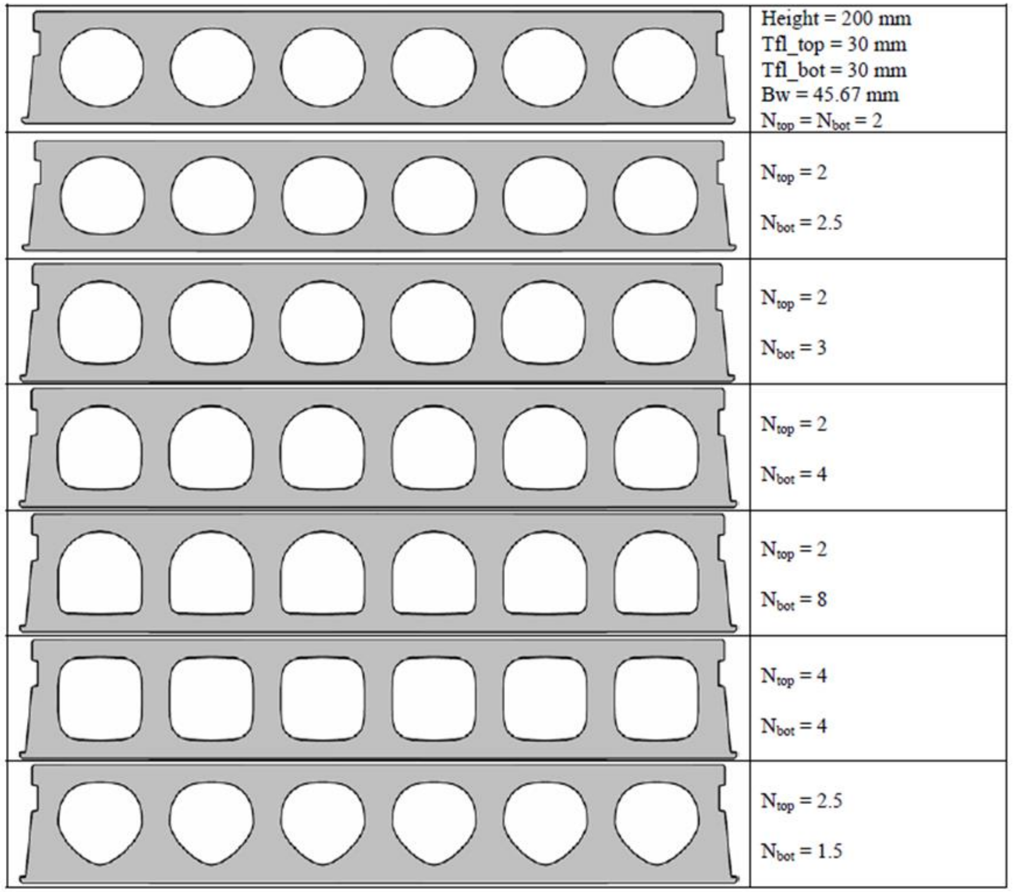

Linha do C.G.
Ponto Crítico
z
zpc
hpc
e
y


CENTRO APOIO
h
ei
linha de ruptura
zpc
y' (CG)
35°
hpc
Ap,i
Ponto Crítico
seções investigadas
xpc
Diagrama de tensões Principais

Estudo da Geometria da Seção Transversal – LINDSTRON (2007) – C6-Fib-TG6.1



Height = 200 mm
Tfl_top = 30 mm
Tfl_bot = 30 mm
Bw = 45.67 mm
$N_{top} = N_{bot} = 2$

$N_{top} = 2$
$N_{bot} = 2.5$

$N_{top} = 2$
$N_{bot} = 3$

$N_{top} = 2$
$N_{bot} = 4$

$N_{top} = 2$
$N_{bot} = 8$

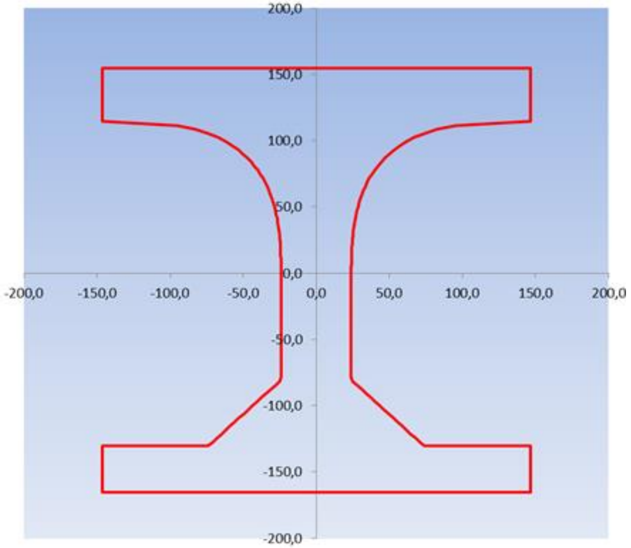
$N_{top} = 4$
$N_{bot} = 4$

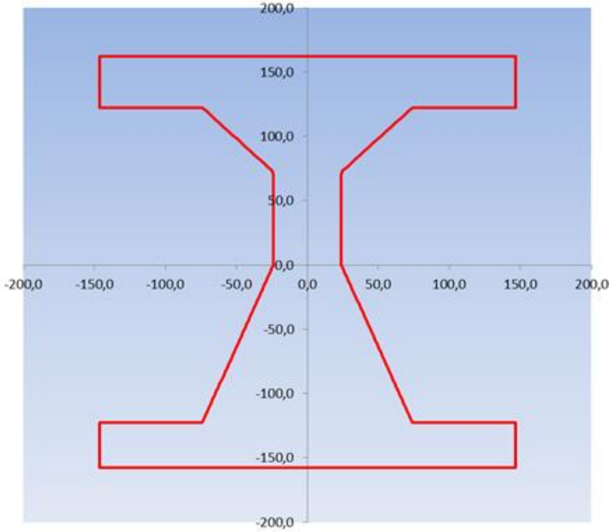
$N_{top} = 2.5$
$N_{bot} = 1.5$

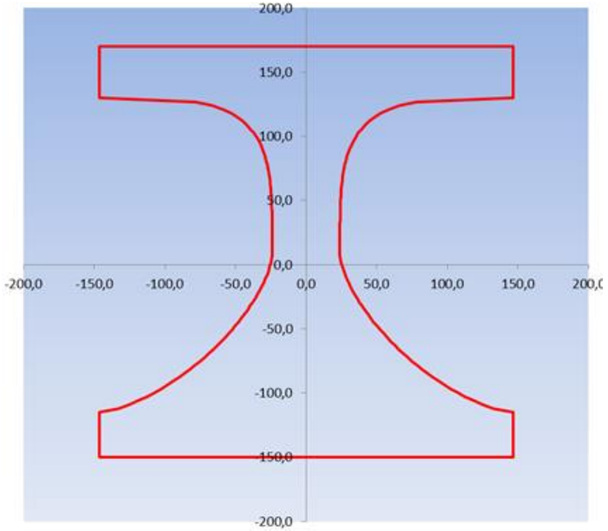
$$\left(\frac{x}{r_h}\right)^N + \left(\frac{z}{r_v}\right)^N = 1$$

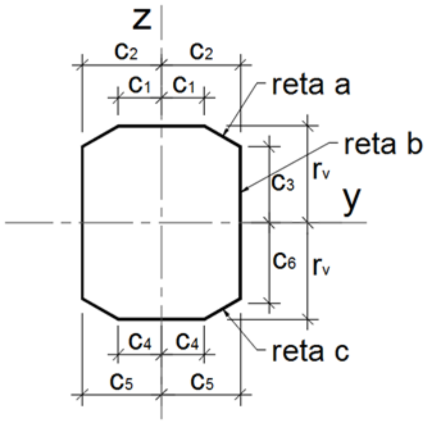
MACIEL (2017)

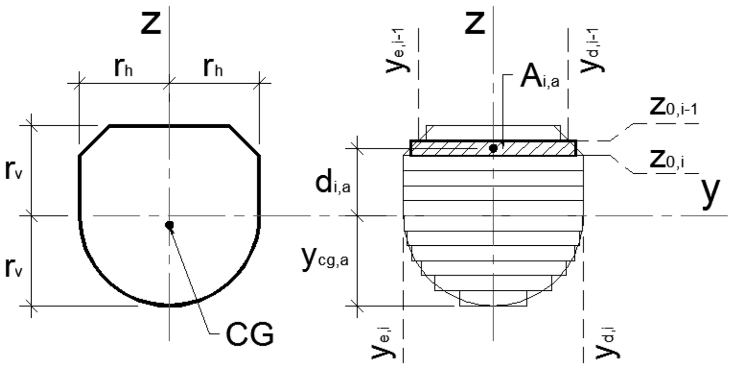
Estudo Numérico da Geometria do Alvéolo – MACIEL (2007) + NETPRE (Chust & Ferreira)

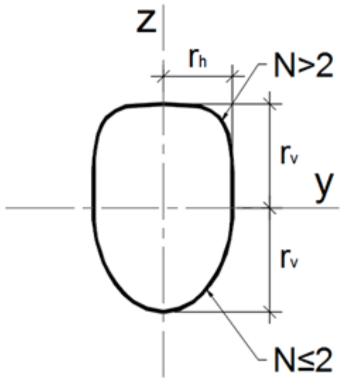












MÉTODO NUMÉRICO PARA GERAÇÃO DAS SEÇÕES

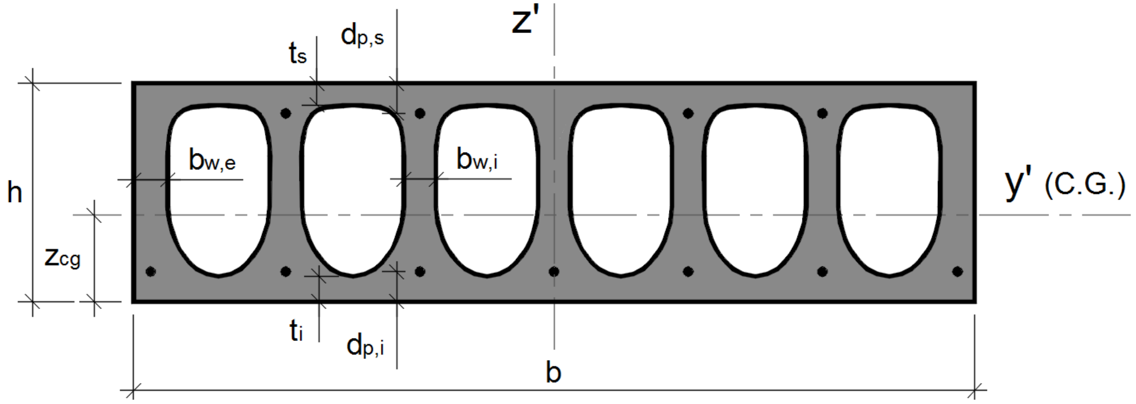
❑ ALVÉOLOS CURVOS

- $$y = \sqrt{r_h \cdot \left[1 - \left(\frac{z}{r_v}\right)^N\right]}\;;\; y \geq 0 \; e \; z \geq 0$$

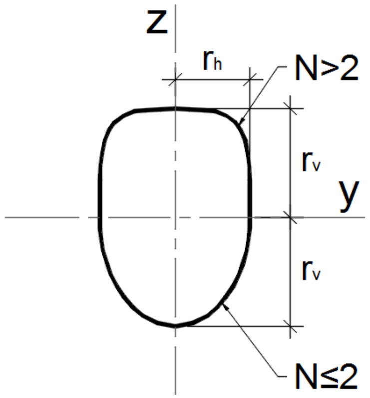
[Lindström (2007)]

$$r_h = \frac{1}{2} \cdot \left\{\frac{b - \left[(n-1) \cdot b_{w,i} + 2 \cdot b_{w,e}\right]}{n}\right\}$$

$$r_v = \frac{1}{2} \cdot \left[h - (t_s + t_i)\right]$$



[Fonte: O autor]



[Fonte: O autor]

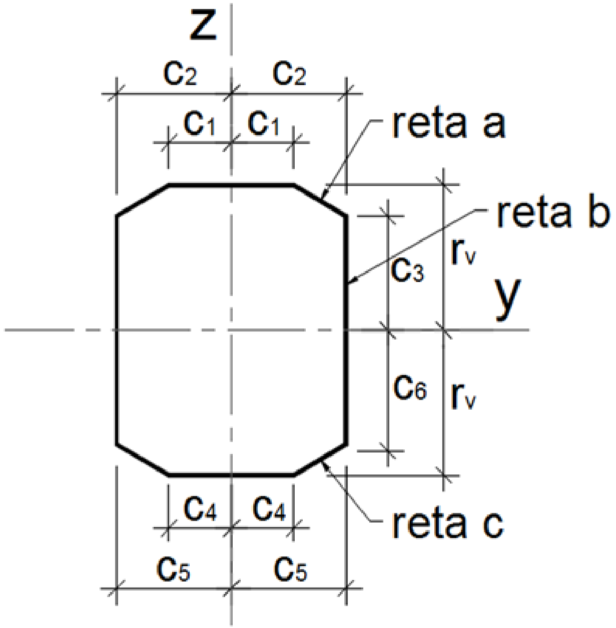
MÉTODO NUMÉRICO PARA GERAÇÃO DAS SEÇÕES

❑ ALVÉOLOS POLIGONAIS

- $c_3 \leq z \leq r_v \rightarrow y = \dfrac{(z - r_v) \cdot (c_2 - c_1)}{(c_3 - r_v)} + c_1$

$$-c_6 < z < c_3 \rightarrow y = \frac{(z + c_6) \cdot (c_2 - c_5)}{(c_3 + c_6)} + c_5$$

$$-r_v \leq z \leq -c_6 \rightarrow y = \frac{(z + r_v) \cdot (c_5 - c_4)}{(-c_6 + r_v)} + c_4$$



[Fonte: O autor]

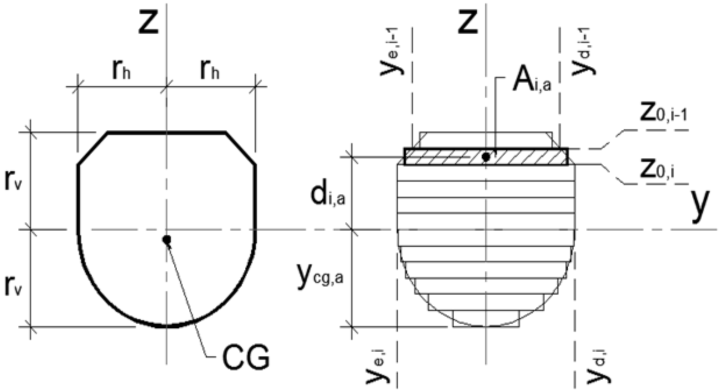
MÉTODO NUMÉRICO PARA GERAÇÃO DAS SEÇÕES

❑ PROPRIEDADES GEOMÉTRICAS DOS ALVÉOLOS

$$A_{i,a} = \frac{1}{2} \cdot \left[\left(y_{d,(i-1)} - y_{e,(i-1)}\right) + \left(y_{d,i} - y_{e,i}\right)\right] \cdot \left|z_{(i-1)} - z_i\right| \qquad A_a = \sum_{i=1}^{k} A_{i,a}$$

$$d_{i,a} = z_{(i-1)} - \frac{1}{2} \cdot \left(z_{(i-1)} - z_i\right) \qquad S_{i,a} = A_{i,a} \cdot d_{i,a} \qquad S_a = \sum_{i=1}^{k} S_{i,a}$$

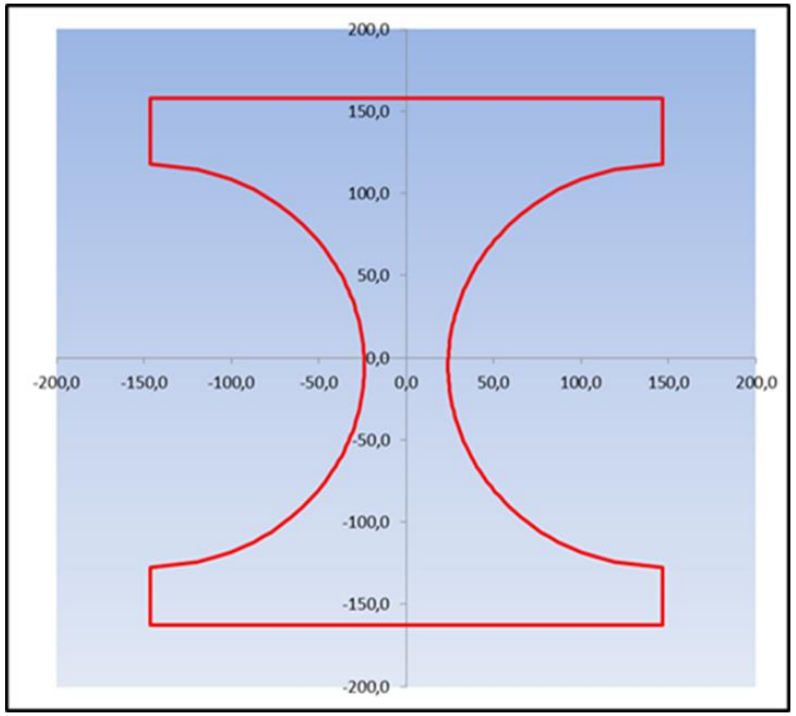
$$z_{cg,a} = \frac{S_a}{A_a} + r_v \qquad I_{y,i,a} = A_{i,a} \cdot \left(d_{i,a}\right)^2 \qquad I_{y,a} = \sum_{i=1}^{k} I_{y,i,a}$$



[Fonte: O autor]

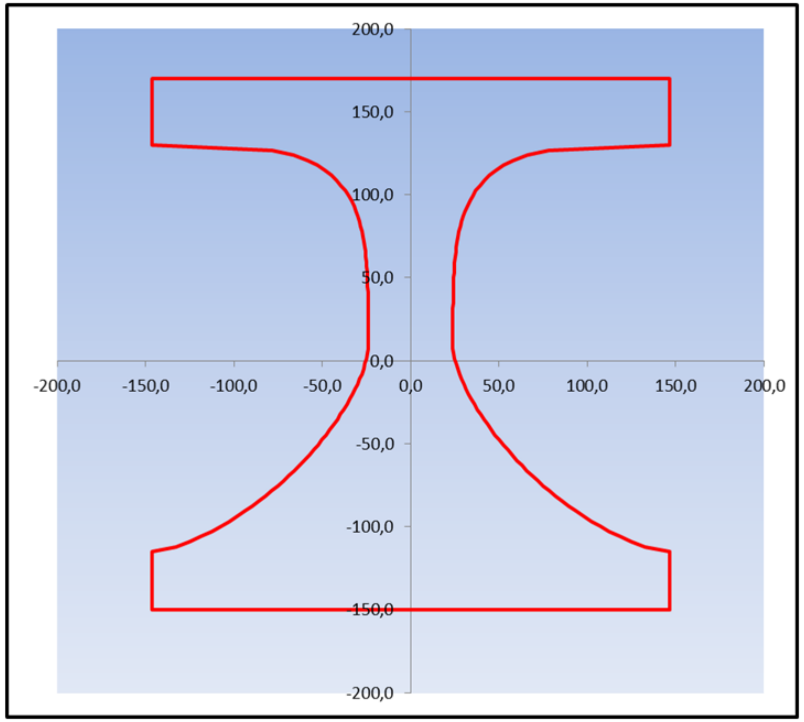
Alvéolo Curvo

$N_s = 2$ / $N_i = 2$



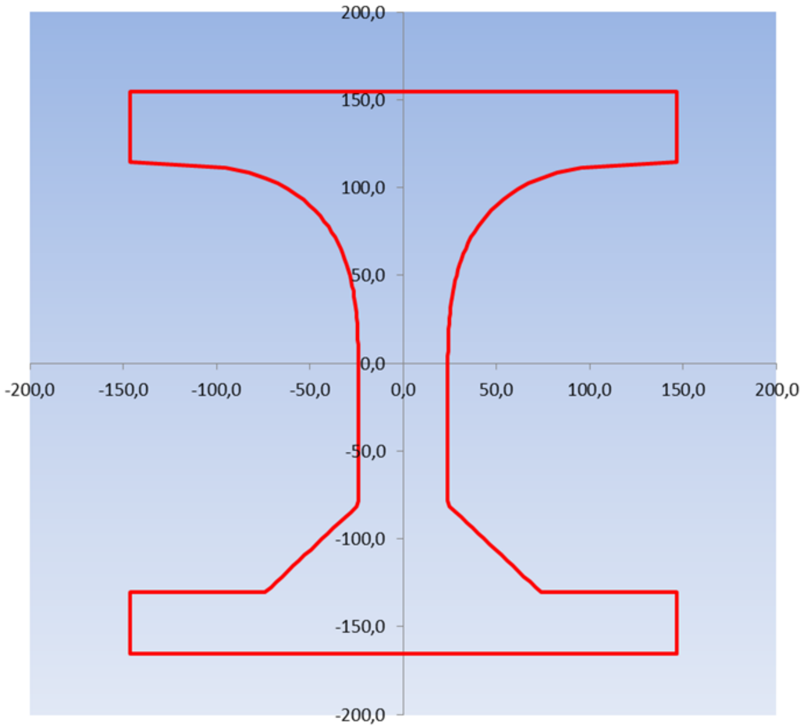
Alvéolo Curvo

$N_s = 4$ / $N_i = 1{,}5$



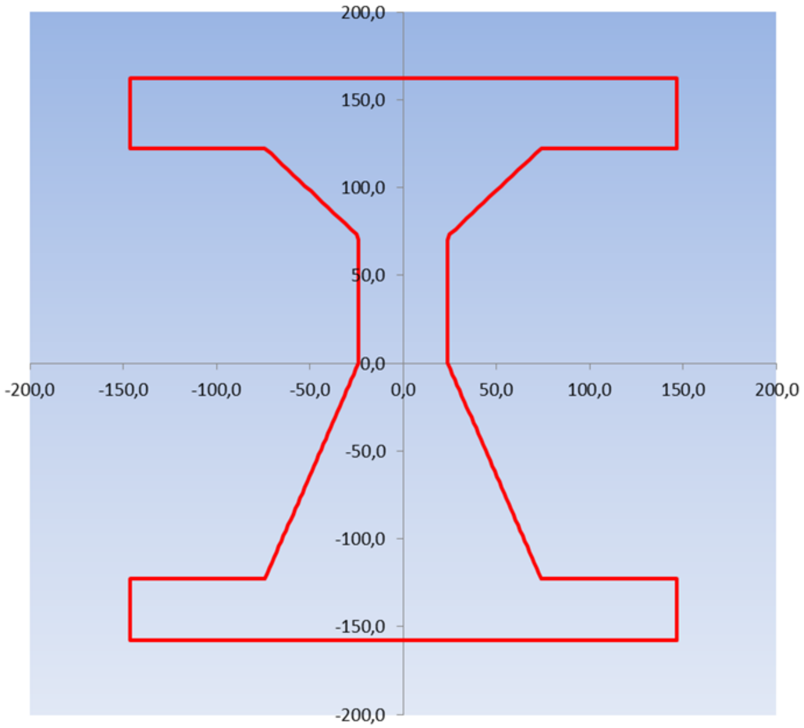
Alvéolo Misto

$N_s = 3$ / $C_4=C_6=$ 72,5mm / $C_5=$112,5mm



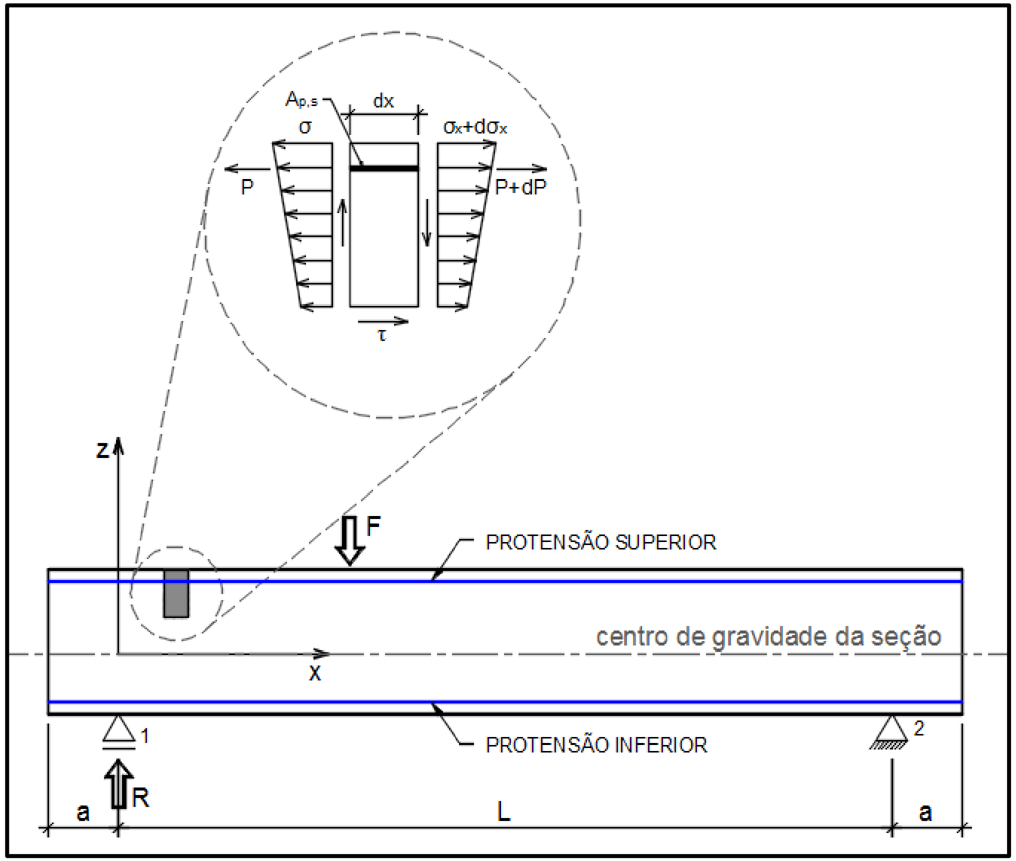
Alvéolo Poligonal

$C_1=C_3=C_4=$ 72,5mm / $C_6=0$ / $C_2=C_5=$112,5mm



ANÁLISE DA RESISTÊNCIA AO CISALHAMENTO EM REGIÕES NÃO FISSURADAS

CÁLCULO DA CORTANTE MÁXIMA RESISTENTE – PAJARI (2005)



[Fonte: Adaptado de PAJARI (2005)]

ANÁLISE DA RESISTÊNCIA AO CISALHAMENTO EM REGIÕES NÃO FISSURADAS

CÁLCULO DA CORTANTE MÁXIMA RESISTENTE – PAJARI (2005)

$$V_{z,máx}=$$

$$\frac{b_{pc}\cdot I_y}{S_{pc}}\cdot\left\{\left[\frac{S_{pc}}{b_{pc}\cdot I_y}\cdot\left(\frac{dP_1}{dx}\cdot e_1-\frac{dP_2}{dx}\cdot e_2\right)-\frac{A_{pc}}{b_{pc}\cdot A}\cdot\left(\frac{dP_1}{dx}+\frac{dP_2}{dx}\right)\right]+\frac{1}{b_{pc}}\cdot\frac{dP_2}{dx}+\frac{b_{pc}}{2\cdot S_{pc}}\cdot f_{ct}\cdot x_{pc}\cdot z_{pc}\right\}+\frac{b_{pc}\cdot I_y}{S_{pc}}$$

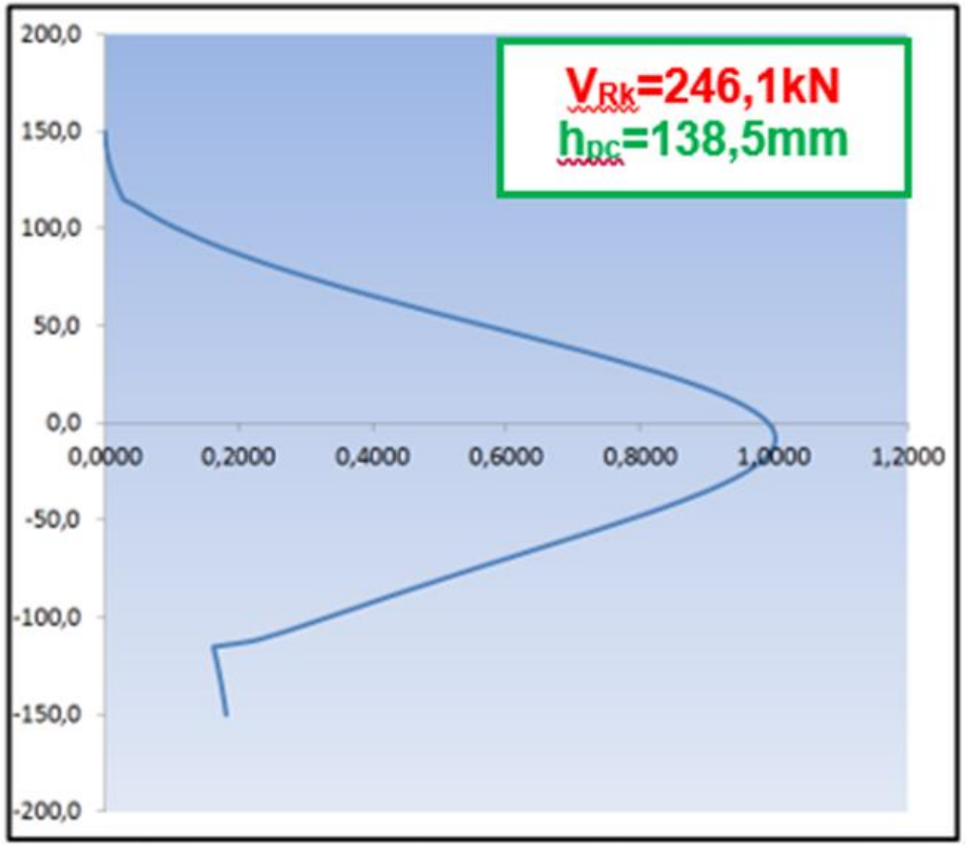
$$\cdot\left\{\left[\left(\frac{dP_1}{dx}\cdot e_1-\frac{dP_2}{dx}\cdot e_2\right)-\frac{A_{pc}\cdot I_y}{A\cdot S_{pc}}\cdot\left(\frac{dP_1}{dx}+\frac{dP_2}{dx}\right)\right]\cdot\frac{f_{ct}}{I_y}\cdot x_{pc}\cdot z_{pc}+\frac{dP_2}{dx}\cdot\frac{f_{ct}}{S_{pc}}\cdot x_{pc}\cdot z_{pc}+\left(\frac{b_{pc}}{2\cdot S_{pc}}\cdot f_{ct}\cdot x_{pc}\cdot z_{pc}\right)^2+f_{ct}\right.$$

$$V_{z,máx}=$$

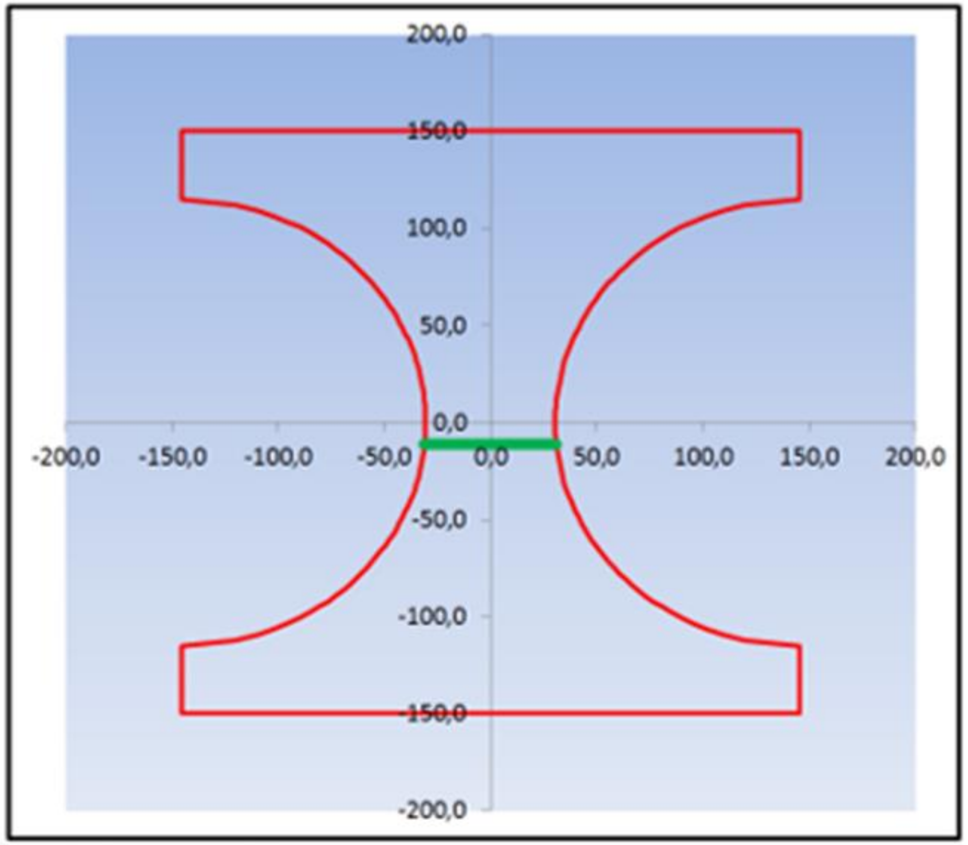
$$\frac{b_{pc}\cdot I_y}{S_{pc}}\cdot\left\{\left[\frac{S_{pc}}{b_{pc}\cdot I_y}\cdot\sum_{i=1}^{n}\left(\frac{dP_i}{dx}\cdot e_i\right)-\frac{A_{pc}}{b_{pc}\cdot A}\cdot\sum_{i=1}^{n}\left(\frac{dP_i}{dx}\right)\right]+\frac{1}{b_{pc}}\cdot\sum_{j=1}^{n}\left(\frac{dP_j}{dx}\right)+\frac{b_{pc}}{2\cdot S_{pc}}\cdot f_{ct}\cdot x_{pc}\cdot z_{pc}\right\}+\frac{b_{pc}\cdot I_y}{S_{pc}}$$

$$\cdot\left\{\left[\sum_{i=1}^{n}\left(\frac{dP_i}{dx}\cdot e_i\right)-\frac{A_{pc}\cdot I_y}{A\cdot S_{pc}}\cdot\sum_{i=1}^{n}\left(\frac{dP_i}{dx}\right)\right]\cdot\frac{f_{ct}}{I_y}\cdot x_{pc}\cdot z_{pc}+\sum_{j=1}^{n}\left(\frac{dP_j}{dx}\right)\cdot\frac{f_{ct}}{S_{pc}}\cdot x_{pc}\cdot z_{pc}+\left(\frac{b_{pc}}{2\cdot S_{pc}}\cdot f_{ct}\cdot x_{pc}\cdot z_{pc}\right)^2+f_{ct}\cdot\frac{1}{A}\right.$$

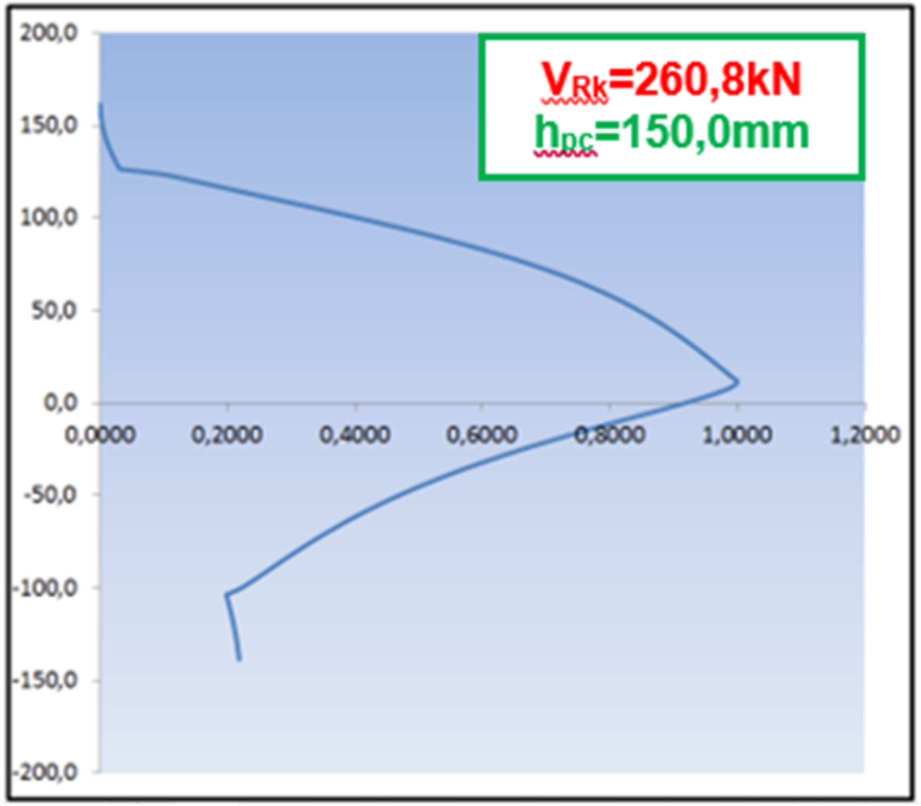
MACIEL (2017) – Proposta de Modificação do Modelo Geral para Resistência à Força Cortante (Tension Shear Capacity) segundo Pajari & Yang


V_{Rk}=246,1kN

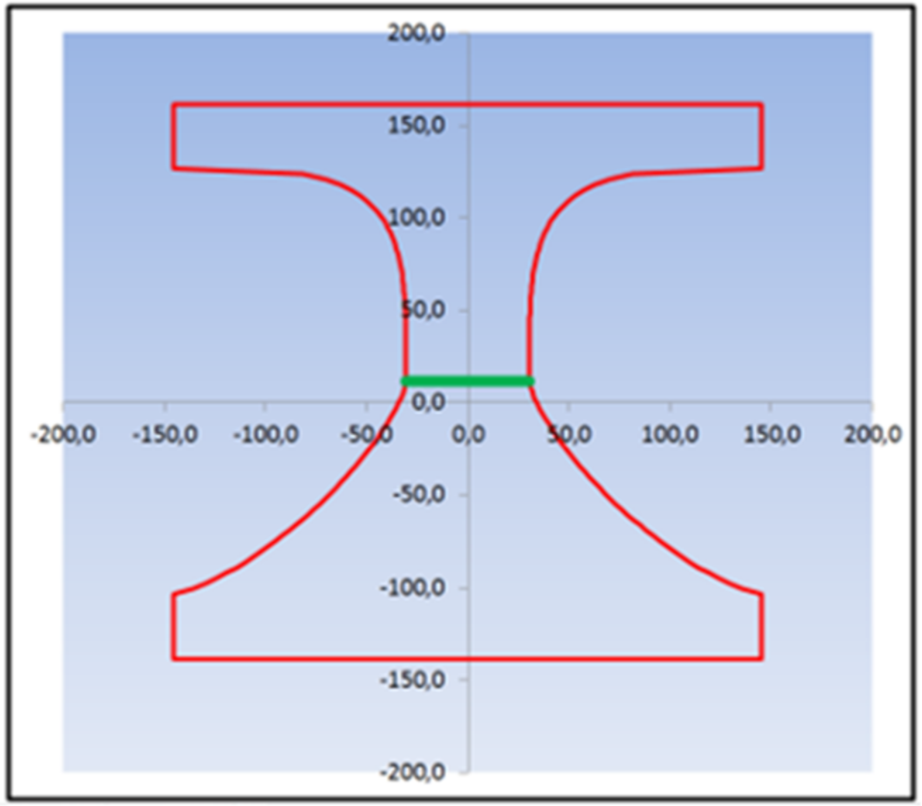
h_{pc}=138,5mm



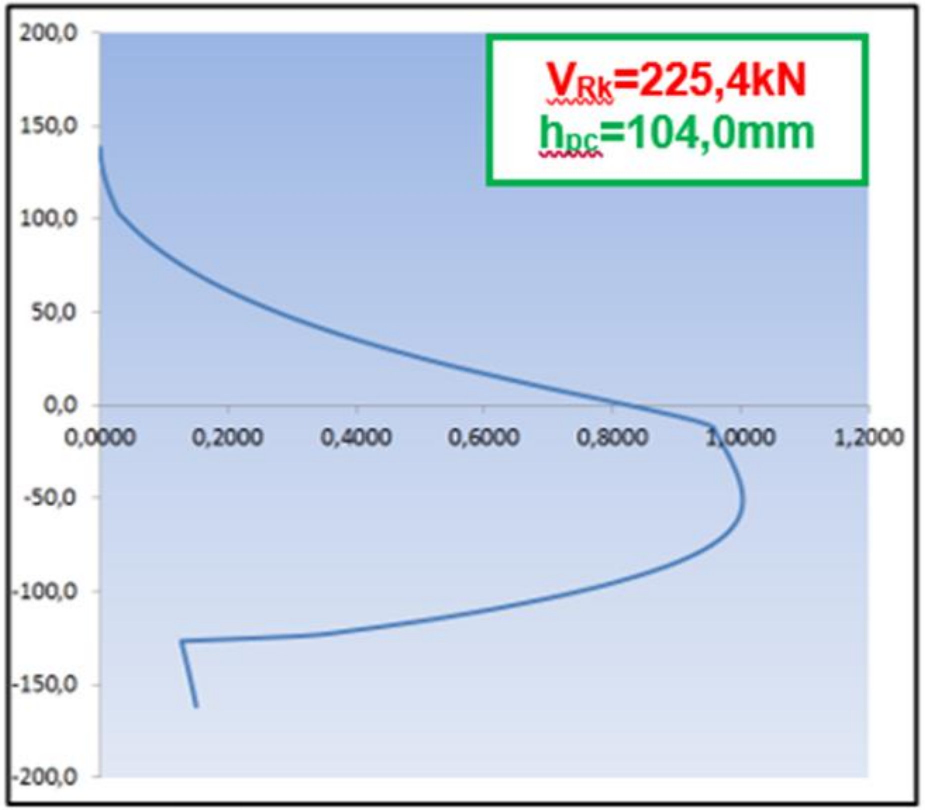
MACIEL (2017) – Proposta de Modificação do Modelo Geral para Resistência à Força Cortante (Tension Shear Capacity) segundo Pajari & Yang

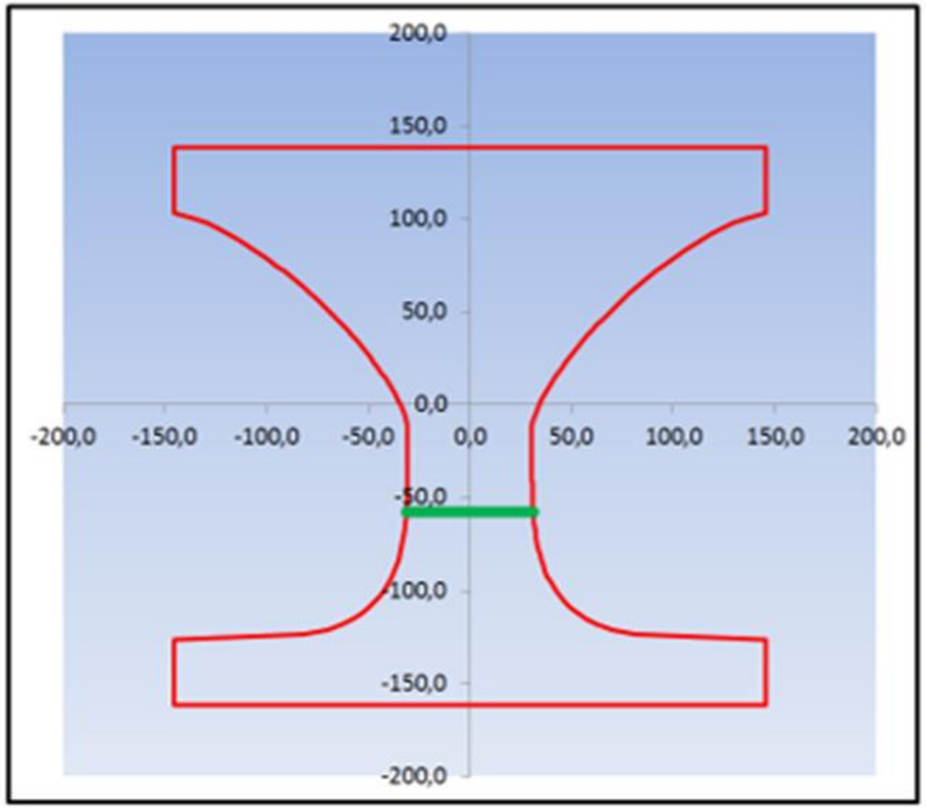


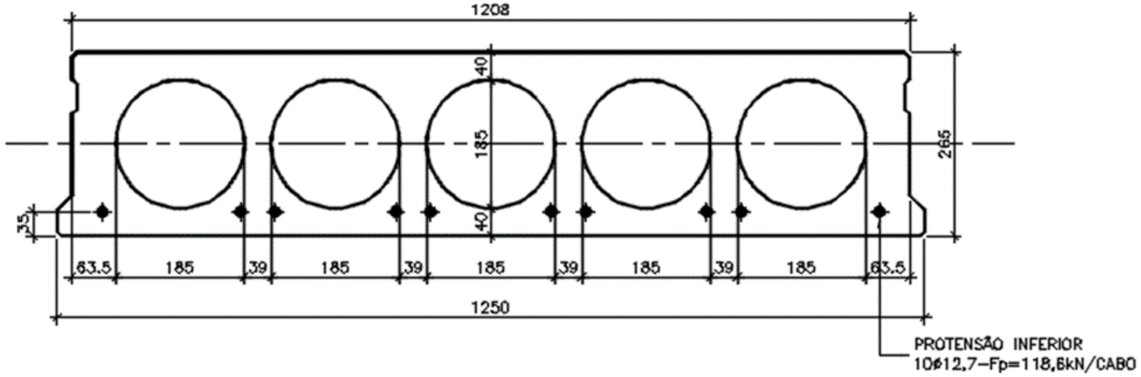
V_{Rk}=260,8kN
h_{pc}=150,0mm

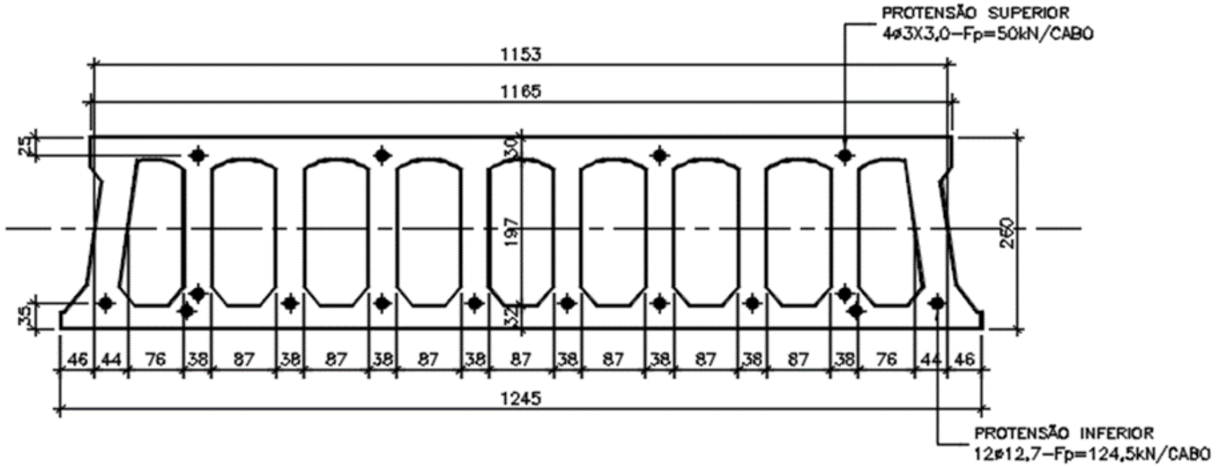


MACIEL (2017) – Proposta de Modificação do Modelo Geral para Resistência à Força Cortante (Tension Shear Capacity) segundo Pajari & Yang


V_{Rk}=225,4kN
h_{pc}=104,0mm







CORTANTE RESISTENTE ($\gamma_c = 1,0$)

Protótipo	$h_{nominal}$ (mm)	$V_{R,exp}$ (kN)	$V_{R,cal}$ (kN)			$V_{R,exp}/V_{R,cal}$	
			(1)	(2)	Diferença	(1)	(2)
Protótipo A	265	233	163,4	172,2	5,4%	1,43	1,35
Protótipo B	260	244	264,2	259,7	1,7%	0,92	0,94

Protótipo A - Alvéolo Circular (LA02-C-A) Protótipo B - Alvéolo Misto (LA05-B)

(1) Seção transversal de projeto (2) Seção transversal real

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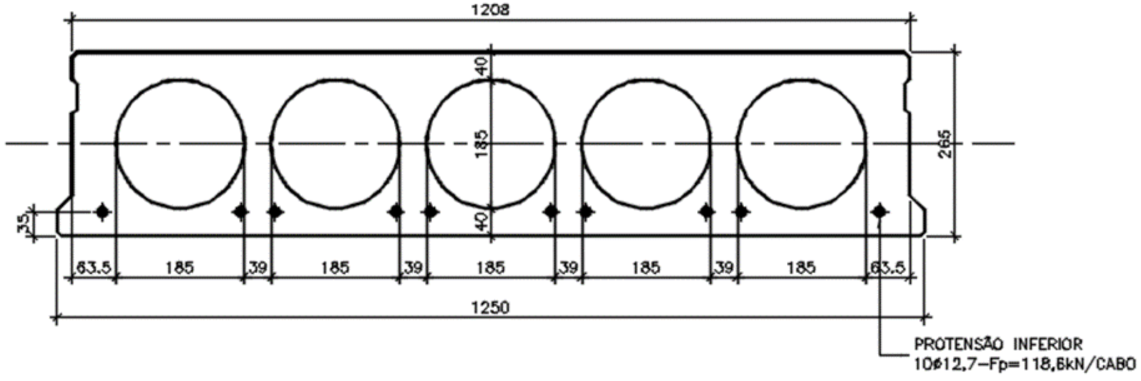
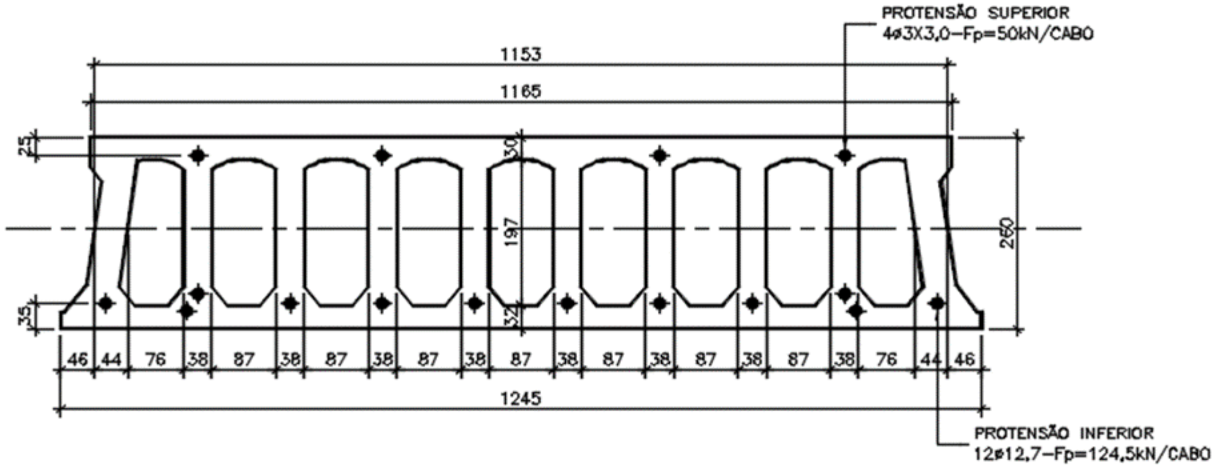




Tension Shear – EC2

$$V_{Rd,c} = \frac{I \cdot b_w}{S} \cdot \sqrt{{f_{ctd}}^2 + \alpha_l \cdot \sigma_{cp} \cdot f_{ctd}}$$

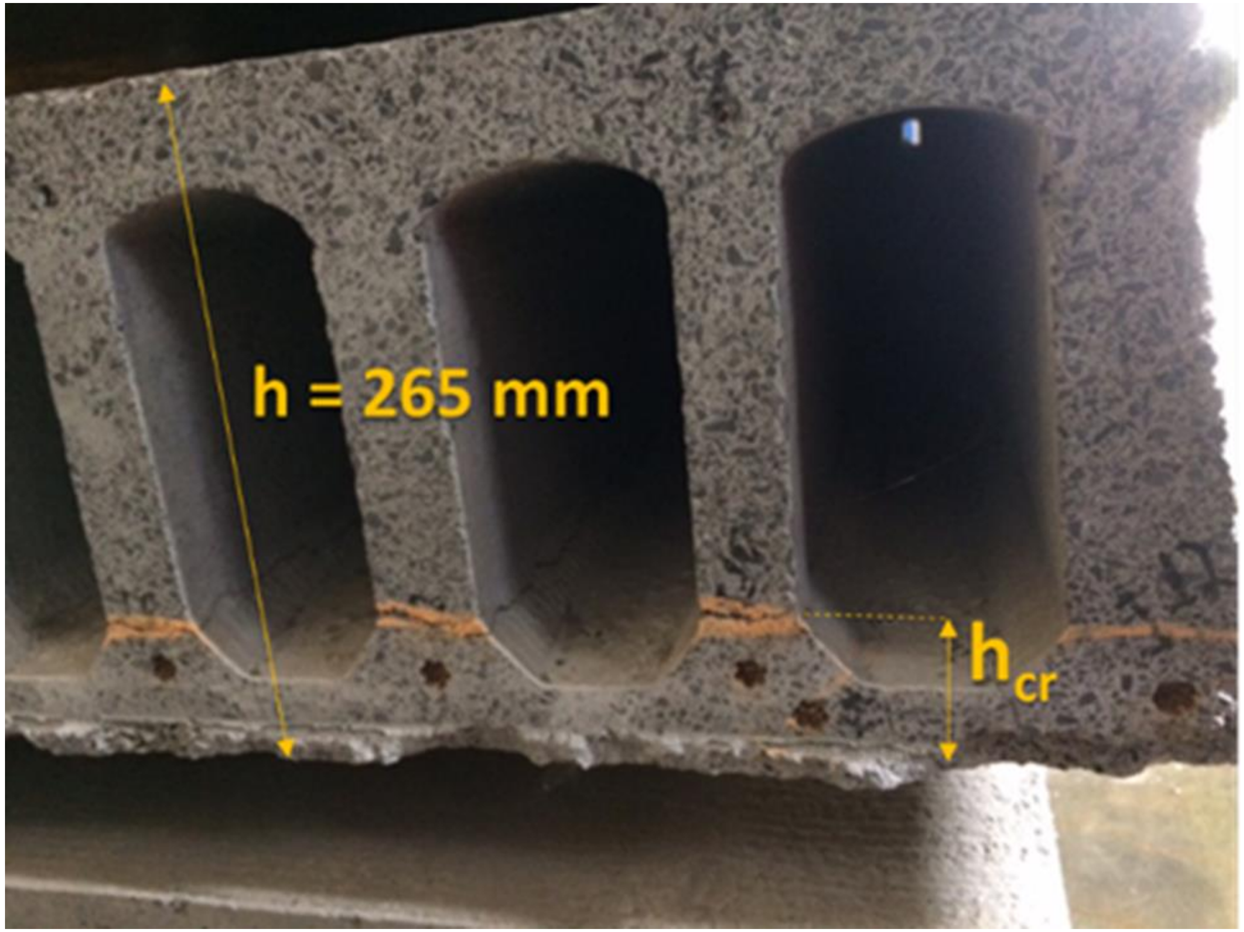
Tension Shear – FIB & EN1168:2005 (improved)

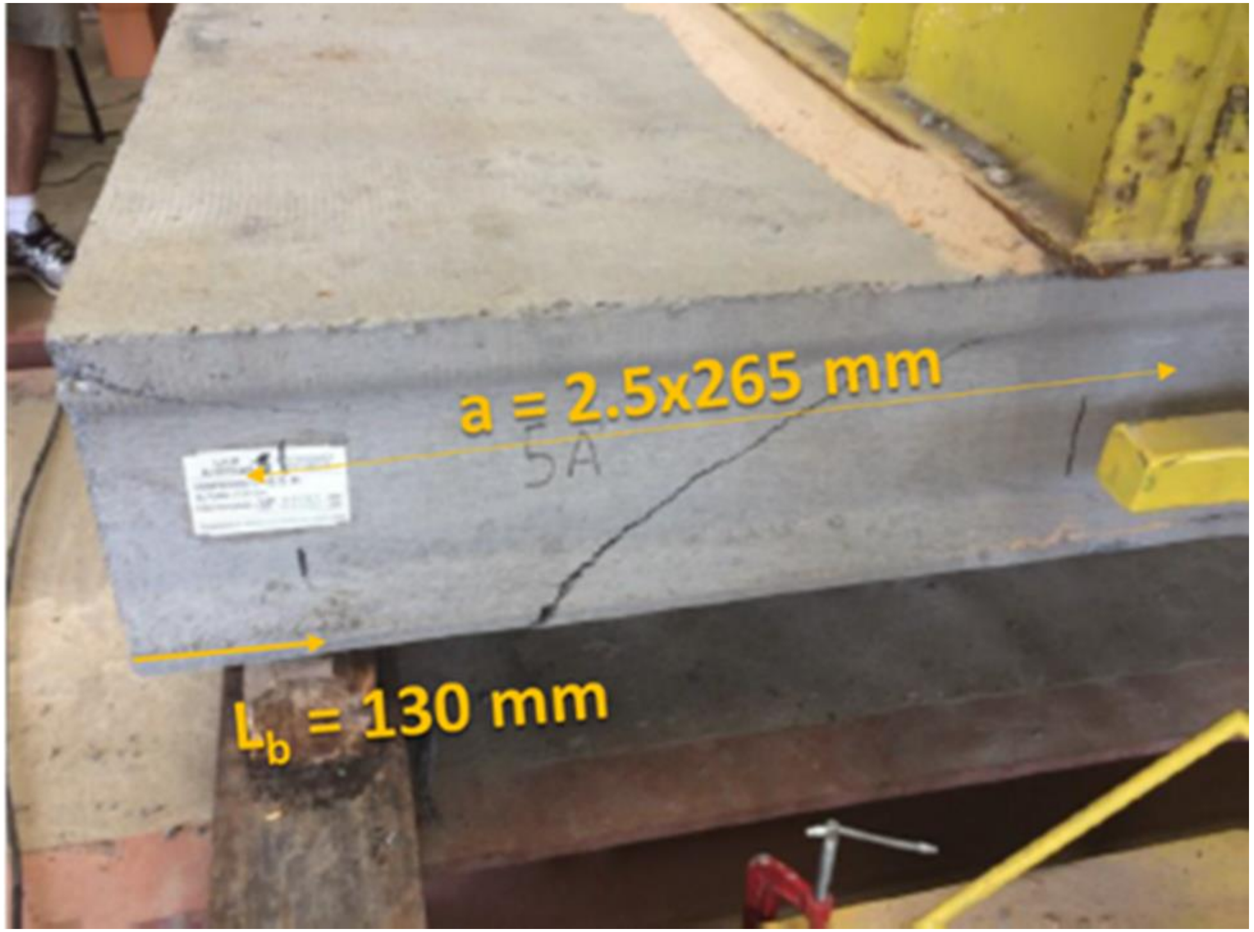
$$V_{Rd,c} = \varphi \cdot \frac{I \cdot b_w}{S_c} \cdot \sqrt{{f_{ctd}}^2 + \beta \cdot \alpha_l \cdot \sigma_{cp} \cdot f_{ctd}}$$

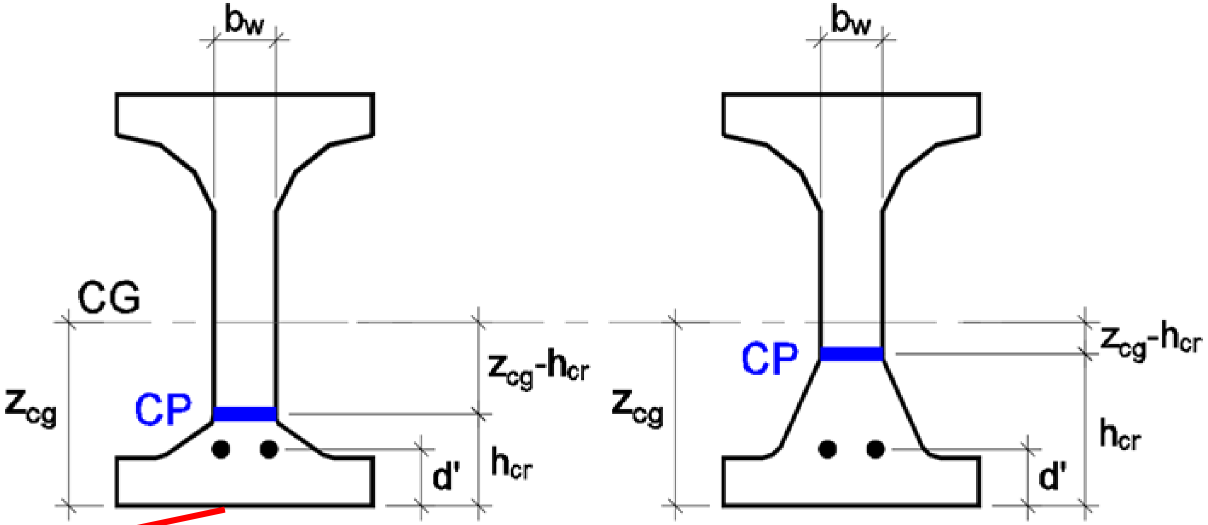
$\varphi=0,8$

$\beta=0,9$

*** PARA LAJES COM ESPESSURA SUPERIOR A 450mm DEVE–SE APLICAR FATOR REDUTOR GLOBAL DE 0,9 ***

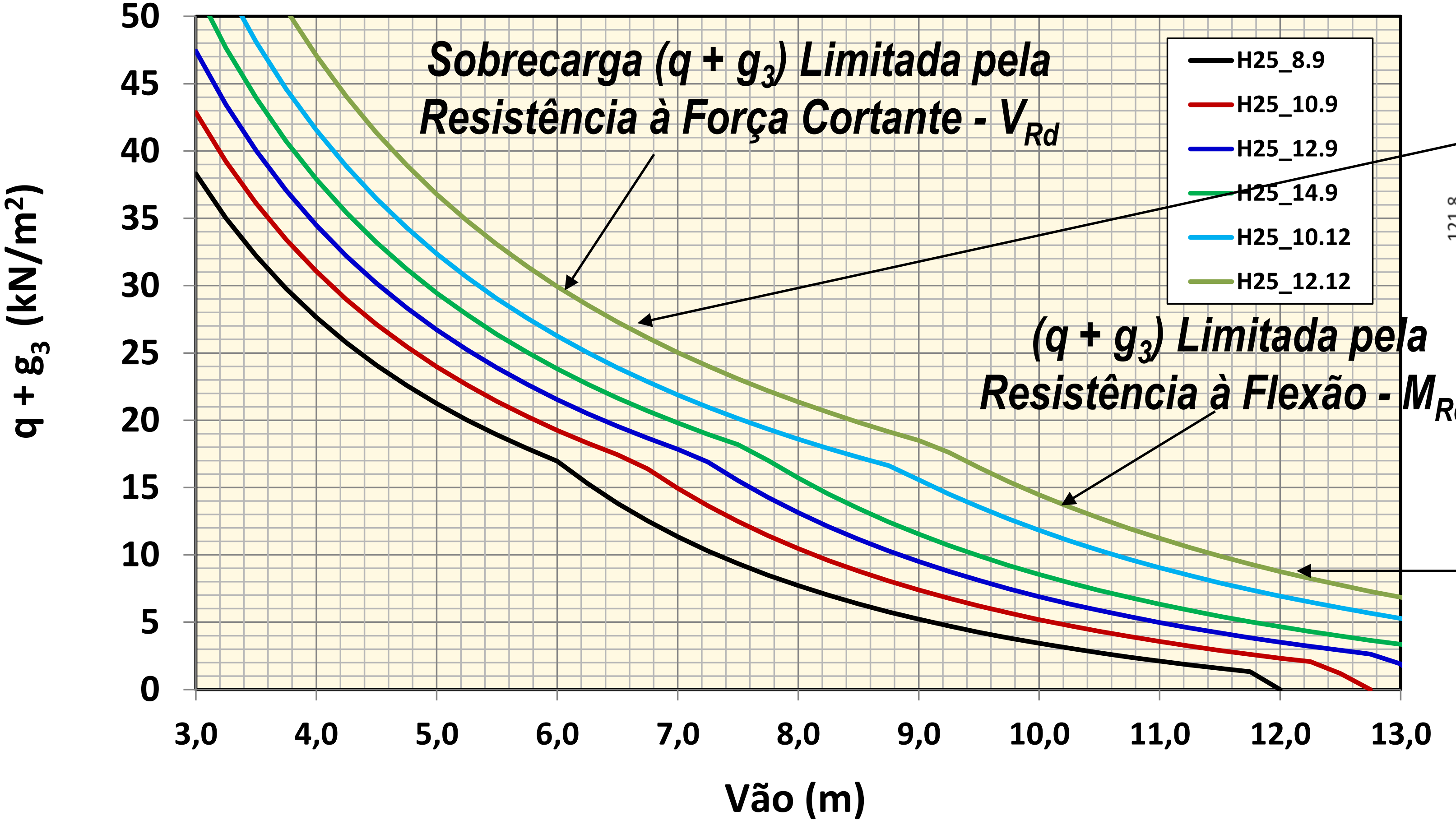

h = 265 mm
h_{cr}


a = 2.5x265 mm
5A
L_b = 130 mm



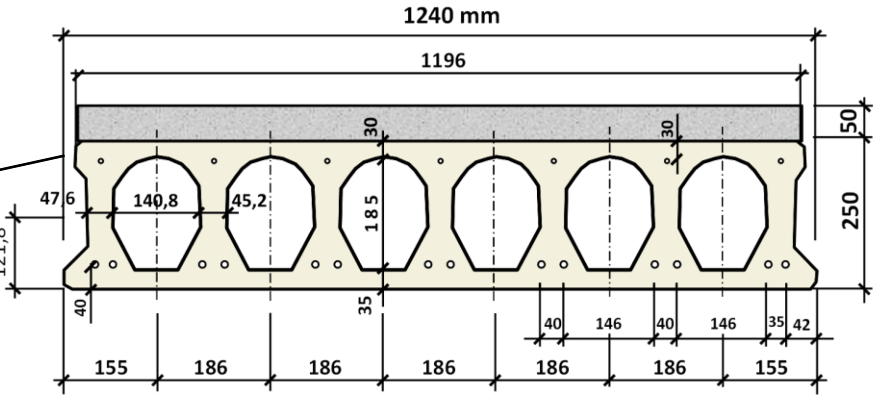
Aumentando h_{crit}, aumenta a resistência à força cortante (Tension Shear Capacity)

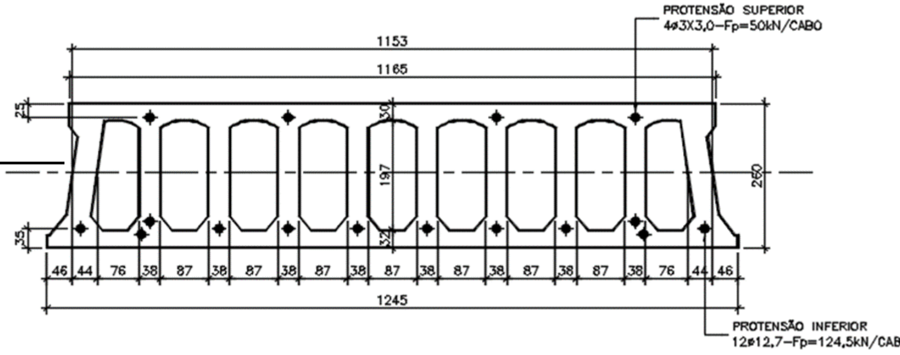
MECANISMOS DE RESISTÊNCIA AO CISALHAMENTO (Situações de Projeto)



Sobrecarga (q + g_3) Limitada pela Resistência à Força Cortante - V_{Rd}

(q + g_3) Limitada pela Resistência à Flexão - M_{Rd}





NETPRE-UFSCar – Ferreira, M.A. (2017)