Introduction to Concrete Beam Design Flow Charts

The concrete beam design flow charts address the following subjects:

- For a rectangular beam with given dimensions: Analyzing the beam section to determine its moment strength and thus defining the beam section to be at one of the following cases:
  - Case 1: Rectangular beam with tension reinforcement only. This case exists if the moment strength is larger that the ultimate (factored) moment.
  - Case 2: Rectangular Beam with tension and compression reinforcement. This case may exist if the moment strength is l ess than the ultimate (factored) moment.
- For T-section concrete beam: Analyzing the beam T -section to determine its moment strength and thus defining the beam section to be one of the following cases:
  - Case 1: The depth of the compression block is within the flanged portion of the beam, i.e, the neutral axis N.A. depth is less than the slab thinness, measured from the top of the slab. This case exists if moment strength is larger than ultimate moment.
  - Case 2: The depth of the compression block is deeper t han the flange thickness, i.e. the neutral axis is located below the bottom of the slab. This case exists if the moment strength of T -section beam is less that the ultimate (factored) moment.
- Beam Section Shear Strength: two separate charts outline in det ails Shear check. One is a basic shear check, and two is detailed shear check, in order to handle repetitive beam shear reinforcement selection. See shear check introduction page for further details.

In any of the cases mentioned above, detailed procedure s and equations are shown within the charts cover all design aspects of the element under investigations, with ACI respective provisions.

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Notations for Concrete Beam Design Flow Charts

a	=	depth of equivalent rectangular stress block, in.
a_b	=	depth of equivalent rectangular stress block at balanced condition, in.
a_{max}	=	depth of equivalent rectangular stress block at maximum ratio of tension-reinforcement, in.
A_s	=	area of tension reinforcement, in^2.
A'_s	=	area of reinforcement at compression side, in^2.
b	=	width of beam in rectangular beam section, in.
b_e	=	effective width of a flange in T-section beam, in.
b_w	=	width of web for T-section beam, in.
c	=	distance from extreme compression fiber to neutral axis, in.
c_b	=	distance from extreme compression fiber to neutral axis at balanced condition, in.
C_c	=	compression force in equivalent concrete block.
C_s	=	compression force in compression reinforcement.
d	=	distance from extreme compression fiber to centroid of tension -side reinforcement.
d'	=	distance from extreme compression fiber to centroid of compression -side reinforcement.
E_s	=	modulus of elasticity of reinforcement, psi.
f'_c	=	specified compressive strength of concre te.
f_y	=	specified tensile strength of reinforcement.
M_n	=	nominal bending moment.
$M_{n\,bal}$	=	moment strength at balanced condition.
M_u	=	factored (ultimate) bending moment.
R_u	=	coefficient of resistance.
t	=	slab thickness in T-section beam, in.
β_1	=	factor as defined by ACI 10.2.7.3.
ε_c	=	concrete strain at extreme compression fibers, set at 0.003.
ε'_s	=	strain in compression-side reinforcement.
ε_y	=	yield strain of reinforcement.
ρ	=	ratio of tension reinforcement.
ρ_b	=	ratio of tension reinforcement at balanced condition.
ρ_f	=	ratio of reinforcement equivalent to compression force in slab of T - section beam.
ρ_{max}	=	maximum ratio of tension reinforcement permitted by ACI 10.3.3.
ρ_{min}	=	minimum ratio of tension reinforcement permitted by ACI10 .5.1.
$\rho_{req'd}$	=	required ratio of tension reinforcement.
ϕ	=	strength reduction factor.

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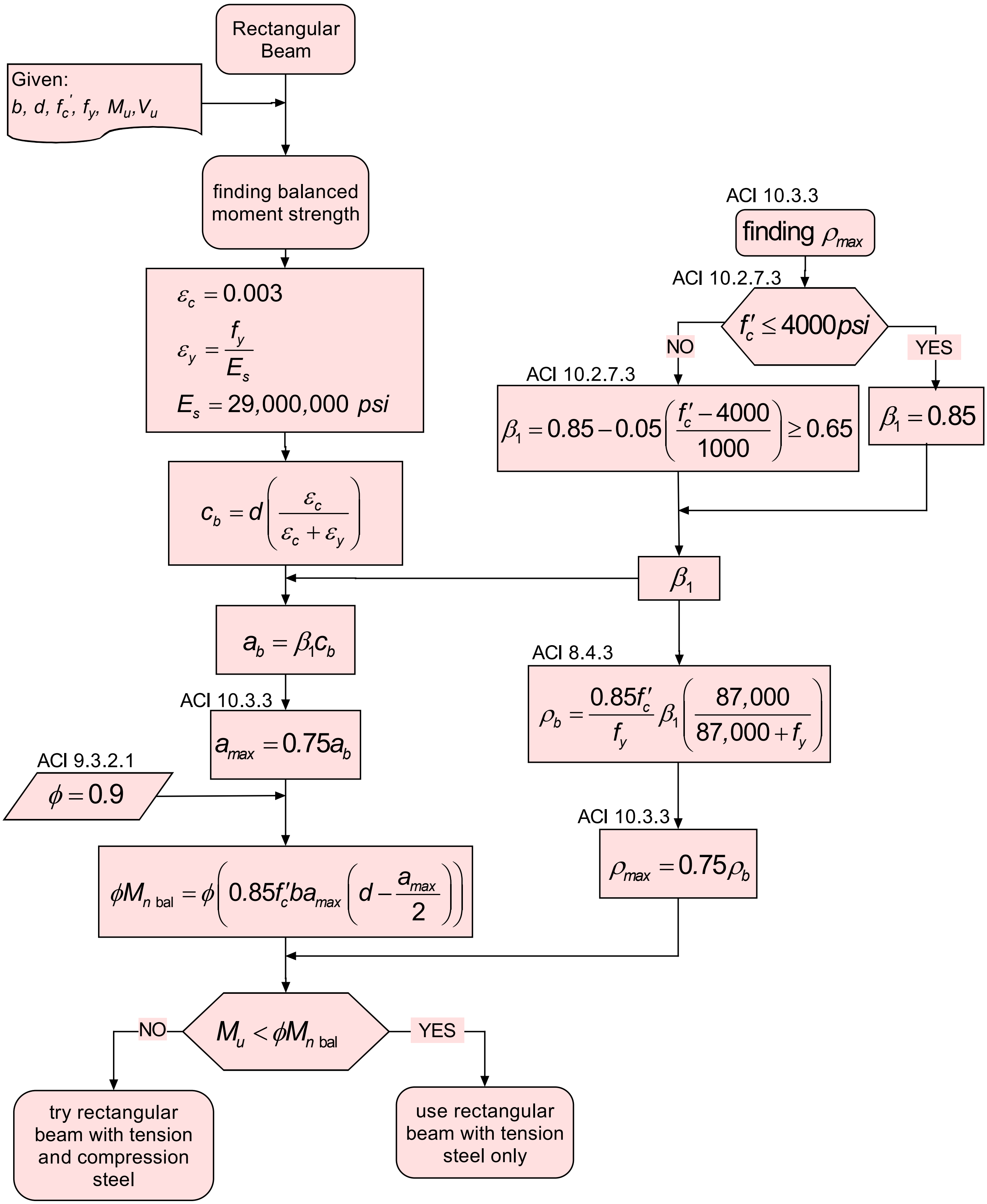
Moment Strength of Rectangular Concrete Beam



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Rectangular Concrete Beam with Tension Reinforcement

rectangular beam with tension steel only

$$R_u = \frac{M_u}{\phi b d^2}$$

$$\rho_{req'd} = \frac{0.85 f'_c}{f_y}\left(1 - \sqrt{1 - \frac{2R_u}{0.85 f'_c}}\right)$$

ACI 10.5.1

$$\rho_{min} = \text{max of} \left| \frac{3\sqrt{f'_c}}{f_y} \quad \frac{200}{f_y} \right\rangle$$

$\rho_{req'd} \geq \rho_{min}$

- NO: $\rho = 1.33\rho_{req'd}$
  - $\rho < \rho_{min}$
    - NO: $\rho = \rho_{min}$
    - YES: $\rho = 1.33\rho_{req'd}$
- YES: $\rho_{req'd} > \rho_{max}$
  - NO: use $\rho = \rho_{req'd}$
  - YES: STOP. go to rectangular beam with tension and compression steel

ACI 10.5.2

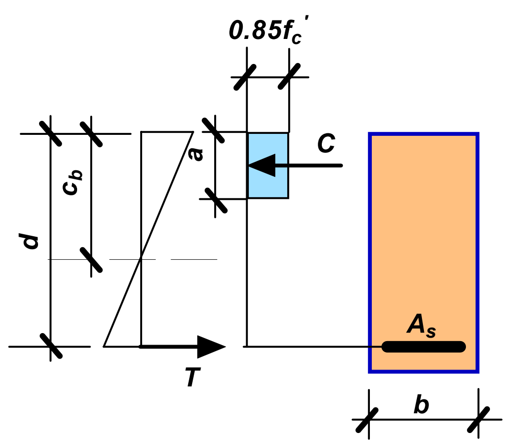
$$A_s = \rho b d$$

select reinforcement, A_s

$$a = \frac{A_s f_y}{0.85 f'_c b}$$

$$\phi M_n = \phi\left(0.85 f'_c b a \left(d - \frac{a}{2}\right)\right)$$

proceed to shear design



Rectangular Beam with Tension & Compression Reinforcement

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rectangular beam with tension and compression steel

$$M'_u = M_u - \phi M_{n_{bal}}$$

$d' = 2.5''$

$$\rho' = \frac{M'_u}{\phi\left(f_y - 0.85 f'_c\right)\left(d - d'\right) bd}$$

$$\rho = \rho_{max} + \rho'$$

steel at tension side → $A_s = \rho bd$

steel at comp. side → $A'_s = \rho' bd$

select reinforcement A_s & A'_s

find the new d

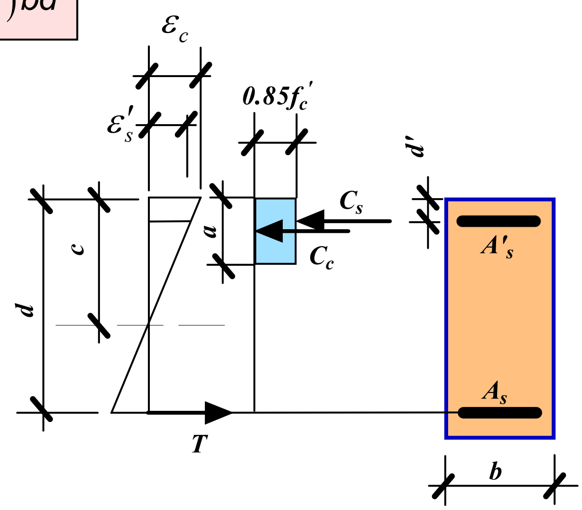
proceed to check compression steel yields

$$a = \frac{\left(A_s - A'_s\right) f_y}{0.85 f'_c b} + \frac{A'_s}{A_s}$$

$$c = \frac{a}{\beta_1}$$

$$\varepsilon'_s = \varepsilon_c \left(\frac{c - d'}{c}\right)$$

1



Rectangular Beam with Tension & Compression Reinforcement (cont.)

1

$$\varepsilon_s' > \varepsilon_y$$

NO

compression steel does NOT yield

compression steel may be neglected, and thus moment strength is calculated based on the tension steel only. Alternatively:

$$c = \frac{\left(A_s f_y - 87A_s'\right) \pm \sqrt{\left(A_s f_y - 87A_s'\right)^2 + 4\left(0.85 f_c' \beta_1 b\right)\left(87 A_s' d'\right)}}{2\left(0.85 f_c' \beta_1 b\right)}$$

$$f_s = E_s \varepsilon_c \left(\frac{c - d'}{c}\right) < f_y$$

$$\phi M_n = \phi\left(0.85 f_c' ba\left(d - \frac{a}{2}\right) + \left[A_s' f_s\left(d - d'\right)\right]\right)$$

YES

compression steel yields

$$C_c = 0.85 f_c' ab$$

$$C_s = A_s'\left(f_y - 0.85 f_c'\right)$$

$$\phi M_n = \phi\left[C_c\left(d - \frac{a}{2}\right) + C_s\left(d - d'\right)\right] \geq M_u$$

alternatively

$$\phi M_n' = A_s' f_y\left(d - d'\right)$$

alternatively

$$\phi M_n = \phi M_{n_{bal}} + \phi M_n' \geq M_u$$

proceed to shear design

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Moment Strength of T-Section Beam

T-Section Beam

finding balanced moment strength @ a=t

Given:
$b_w, b_e, d, f'_c, f_y, M_u\ V_u$

let a=t

$$C_c = 0.85 f'_c b_e t$$

ACI 9.3.2.1

$$\phi = 0.9$$

$$\phi M_n = \phi C_c \left(d - \frac{t}{2} \right)$$

ACI 10.3.3

finding ρ_{max}

ACI 10.2.7.3

$f'_c \le 4000 psi$

NO:

ACI 10.2.7.3

$$\beta_1 = 0.85 - 0.05 \left(\frac{f'_c - 4000}{1000} \right) \ge 0.65$$

YES:

$$\beta_1 = 0.85$$

$$\beta_1$$

ACI 8.4.3

$$\rho_b = \frac{0.85 f'_c}{f_y} \beta_1 \left(\frac{87{,}000}{87{,}000 + f_y} \right)$$

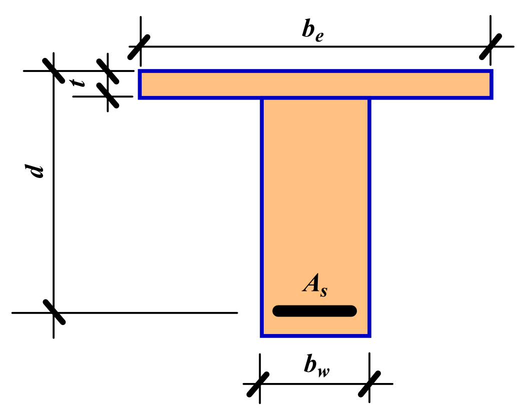
$$\rho_f = \frac{0.85 f'_c (b_e - b_w) t}{f_y b_w d}$$

$$\rho_{max} = 0.75 \frac{b_w}{b_e} (\rho_b + \rho_f)$$

$M_u < \phi M_n$

NO: use T-Section case 2

YES: use T-Section case 1



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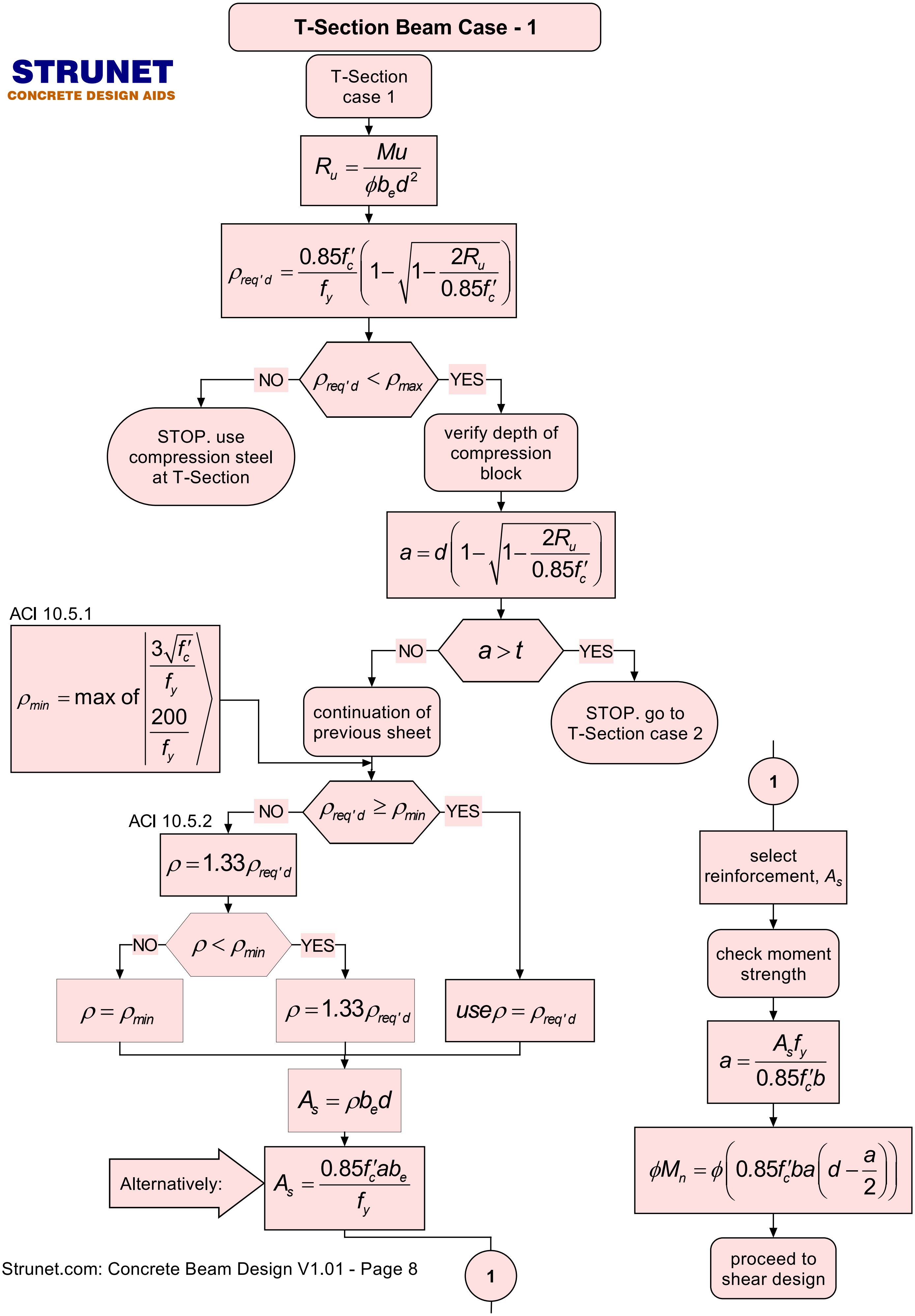

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T-Section Beam Case - 2

T-Section case 2

↓

$$a = d - \sqrt{d^2 - \left(\frac{2M_u}{0.85 f'_c \phi b_w} - \frac{2t\left(b_e - b_w\right)\left(d - 0.5t\right)}{b_w} \right)}$$

↓

$$A_{s_{req'd}} = \frac{0.85 f'_c}{f_y}\left[a b_w + t(b_e - b_w)\right]$$

↓

$$A_{s_{max}} = \rho_{max} b_e d$$

↓

$$A_{s_{req'd}} \geq A_{s_{max}}$$

- NO → STOP. revise to include compression steel
- YES → select reinforcement, A_s

↓

$$a = \frac{A_s f_y}{0.85 f' b_w} - \frac{t}{b_w}\left(b_e - b_w\right)$$

↓

$$C_{c1} = 0.85 f'_c b_w a$$

↓

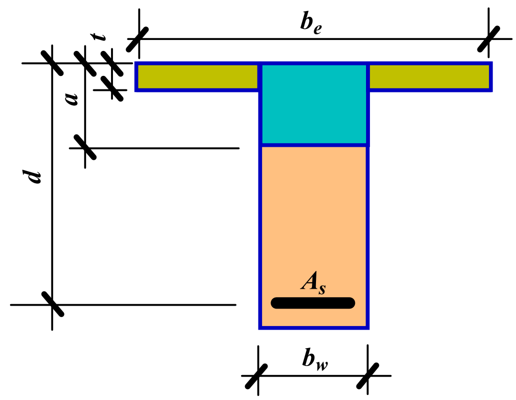
$$C_{c2} = 0.85 f'_c t\left(b_e - b_w\right)$$

↓

$$\phi M_n = C_{c1}\left(d - \frac{a}{2}\right) + C_{c2}\left(d - \frac{t}{2}\right) \geq M_u$$

↓

proceed to shear design



Introduction to Concrete Beam Shear Design

Concrete Beam Shear Design

Introduction and discussion:

The approach of the beam shear check chart is to define the nominal shear strength of the concrete, then compare it with the ultimate shear force at the critical section, and subsequent sections. Shear reinforcement calculation is performed, where applicable.

The shear charts are presented into two parts. One is the Shear Basic Chart, which is outlining the main procedures of the shear design in accordance with ACI applicable code provisions. The second, Shear Detailed Chart, is outlining the steps required for repetitive shear check. The detailed charts provide as much variables and or scenarios as needed to facilitate the creation of automated shear check applications.

The concept in selecting stirrups is based on an input of the bar diameter (d_b) of the stirrups to be used, usually #3, 4, or 5, as well as the number of legs and thus finding the spacing (s) required.

The shear chart intentionally did not include the following ACI provisions due to p ractical and economical justifications:

- Detailed method of ACI §11.3.2.1 for calculating nominal shear strength of concrete, v_c . The reason is the value $V_u d/M_u$ is not constant along the beam span. Although the stirrups spacing resulting from the detailed method may be 1.5 larger than that of the direct method using ACI 11.3.1.1 at the critical section only, the use of the detailed method is not practically justified beyond this critical section, i.e. beyond distance d from the face of support.
- Shear reinforcement as inclined stirrups per §11.5.6.3, and bent up bars per §11.5.6.4 and §11.5.6.5. Only vertical stirrups per §11.5.6.2 are used, since other types of shear reinforcement are not economically justified.

Notations for Concrete Beam Shear Design

b_w	=	Width of beam (web)
d	=	flexural depth of the beam, in.
f'_c	=	concrete compressive strength
f_{ct}	=	average splitting tensile strength of lightweight concrete
f_y	=	reinforcement yield strength
L	=	beam clear span, from support face to other support face.
N	=	number of stirrups required within a given segment of the beam
N_l	=	number of legs for each stirrup
V_c	=	concrete nominal shear strength
V_s	=	nominal shear strength provide by the shear reinforcement
V_{sb}	=	nominal shear strength provided by shear reinforcement at the section where *Vs* is the max permitted by ACI 11.12.1.1 . locating of this section is needed to define which maximum s provisions applies, i.e. §11.5.4.1 or §11.5.4.3
$V_{s\ req'd}$	=	required nominal shear strength provided by shear reinforcement.
V_u	=	factored shear force at the face of the beam support
$V_{u\ d}$	=	factored shear force at distance *d* from the face of the support in accordance with §11.3.1.1 this is the critical shear force provided that: • support is subjected to compressive force. • no concentrated load on the beam within the distance *d*.
$V_{u\ req'd}$	=	factored shear force at the mid-span of the beam, will not be zero if the beam is partially loaded with superimposed loads (i.e. live load on half the beam span)
$\phi V_{n\ max}$	=	reduced shear strength of the beam section located along the beam span where minimum shear reinforcement is required in accordance with §15.5.5.1
s_1	=	spacing of stirrups within the critical section.
s_k	=	spacing of stirrups within any section subsequent to the critical section.
s_{max}	=	maximum stirrups spacing permitted by §11.5.4.1 or §11.5.4.3
$s_{req'd}$	=	required stirrups spacing at the section considered
x_b	=	the distance along the beam at which V_{sb} occurs. for any beam section within the distance x_b, V_{sb} is based on §11.5.4.3, otherwise is based on §11.5.4.1
x_{min}	=	distance from the face of the support along the beam span after which minimum shear reinforcement in accordance to §11.5.5.1 is no longer required.
x_{max}	=	distance from the face of the support along the beam span after which stirrups shall be placed with the maximum spacing per §11.5.4.1, and §11.5.4.3
Δs	=	incremental in stirrups spacing between the subsequent sections, suggested to be 1, 2, and or 3 inches

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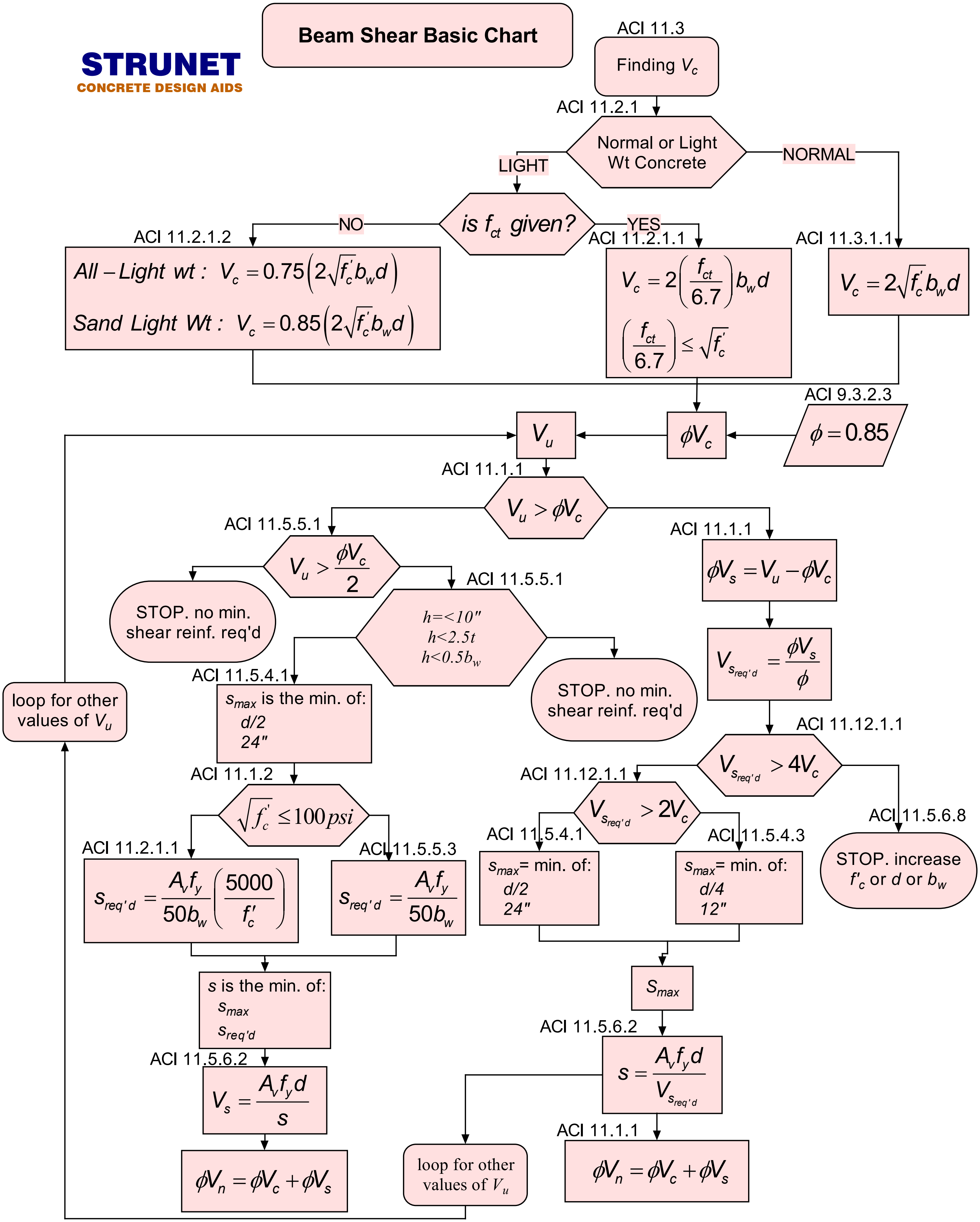

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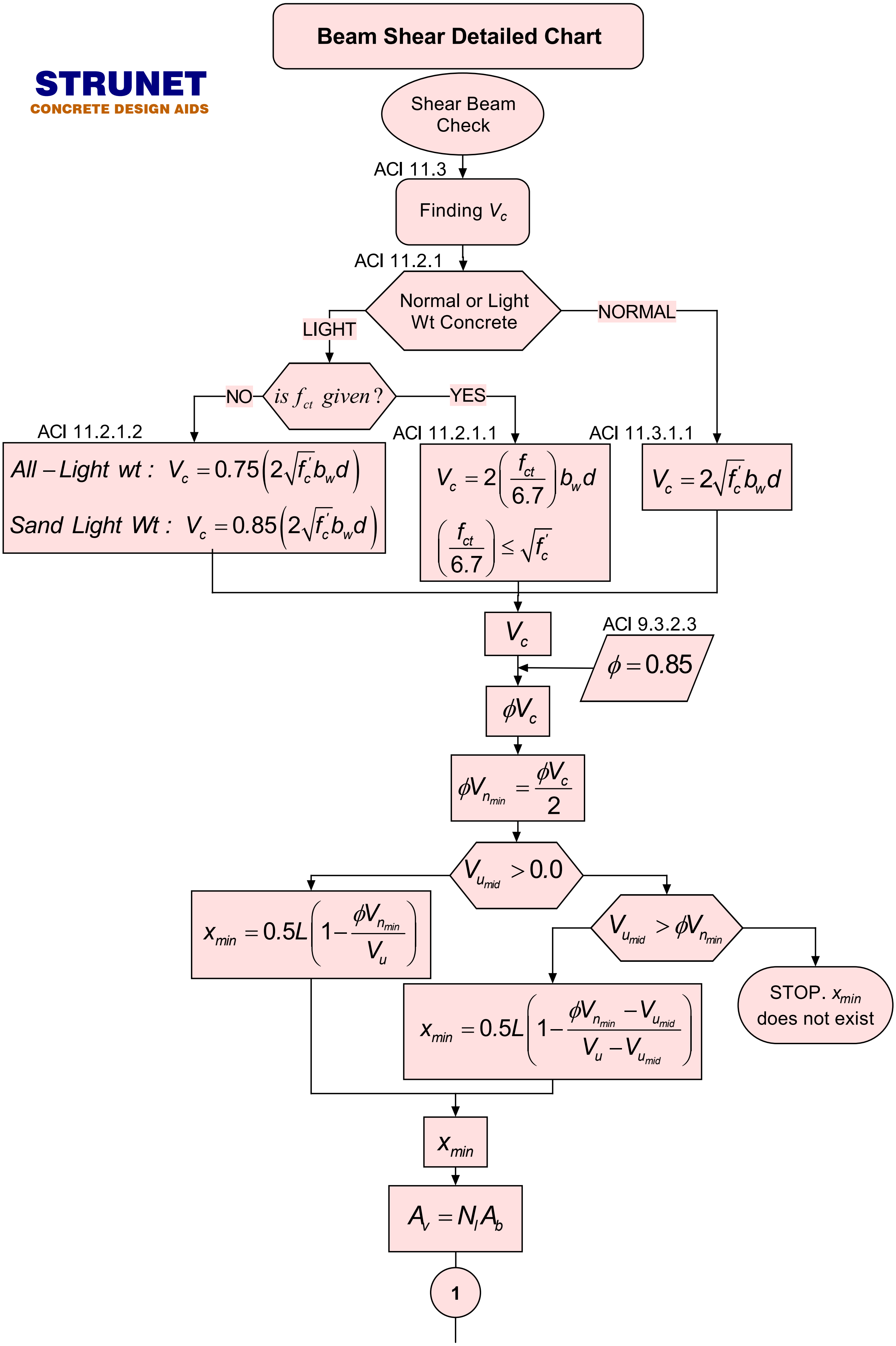

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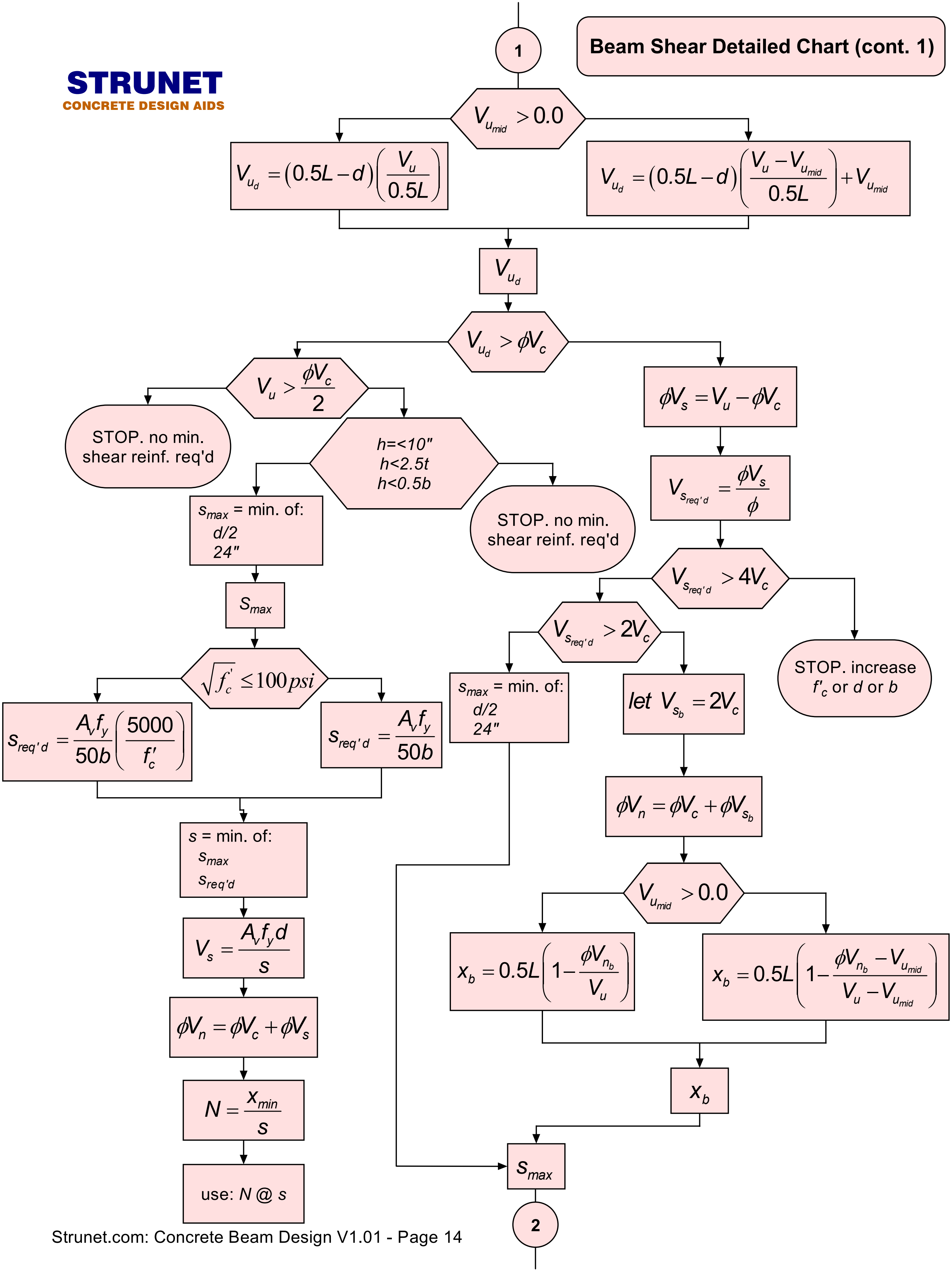
Beam Shear Detailed Chart (cont. 1)



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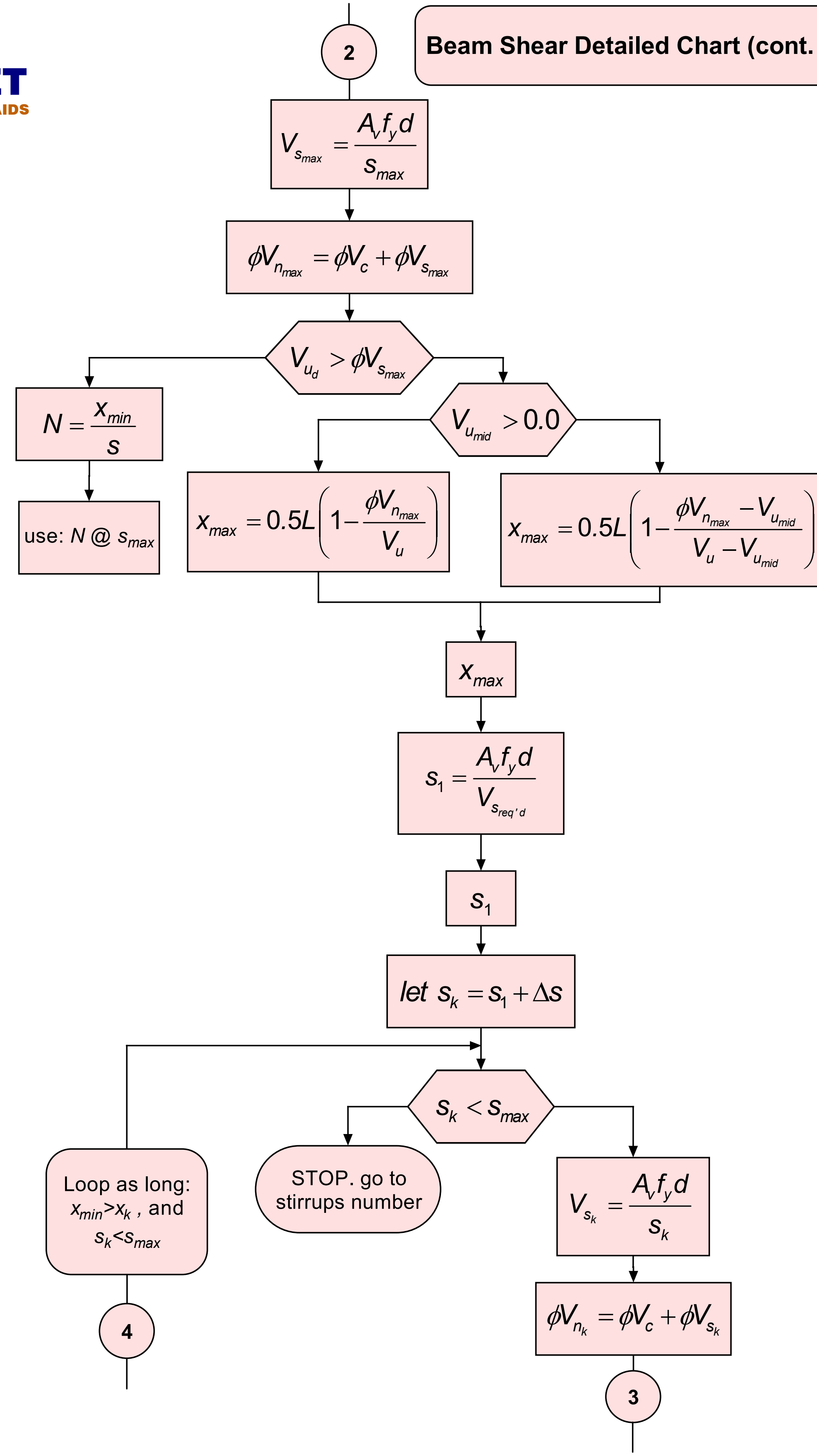
Beam Shear Detailed Chart (cont. 2)



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Beam Shear Detailed Chart (cont. 3)