CHAPTER 9

STRENGTH CAPACITY OF STRUTS, TIES AND NODES

Article 40. Strength capacity of struts, ties and nodes

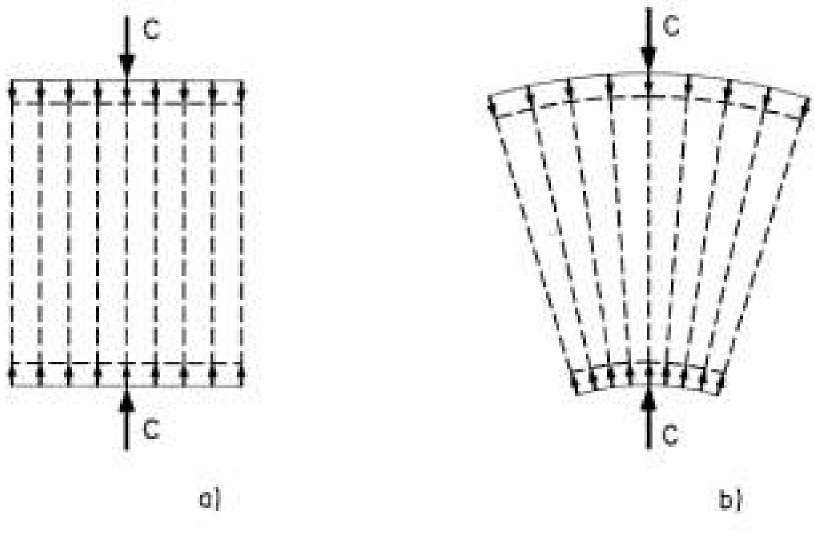
40.1 General

The struts-and-ties model is a suitable procedure for explaining the performance of structural concrete elements in both B and D regions (Article 24.).

The elements of a struts-and-ties model comprise struts, ties and nodes.

Ties usually comprise active or passive reinforcements.

A strut can represent a compression stress-field of uniform width, as shown in figure 40.1.a, or a fan-shaped compression stress-field of variable width, as shown in figure 40.1.b.



Figures 40.1.a and b

A node is an area where the compression stress-fields or tie tensions intersect.

This Article describes the criteria for verifying each of these elements at Ultimate Limit State.

Although the criteria provided in this Chapter comprise verifications at Ultimate Limit State, they do not imply automatic verification of the Limit State for Cracking, several limitations are defined herein which, together with the general principles provided in Article 24, ensure suitable crack control in practice,.

40.2 Strength capacity of ties comprising reinforcements

It will be assumed that the reinforcement reaches design stress at Ultimate Limit State, i.e.

– in the case of passive reinforcements $\sigma_{sd} = f_{yd}$

– in the case of active reinforcements $\sigma_{pd} = f_{pd}$

When compatibility conditions are not explicitly investigated, the maximum strain in struts at Ultimate Limit State shall need to be limited, thus simultaneously indirectly limiting the tensions in the reinforcement Serviceability Limit State.

The carrying capacity of a strut comprising reinforcements may be expressed as:

$$As\ f_{yd} + Ap\ f_{pd}$$

In which:

A_s Cross-section of the passive reinforcement
A_p Cross-section of an active reinforcement.

40.3 Strength capacity of struts

The capacity of a compressed strut is greatly influenced by the tensions and strains which are transverse to the compression stress-field and cracks present.

40.3.1 Concrete struts in regions with uniaxial compression

This is the case of the compression flange of a beam, due to bending stresses, the strength capacity of which can be evaluated from the stress-strain diagrams indicated in 39.5, where the maximum stress for the compressed concrete is limited to:

$$f_{lcd} = f_{cd}$$

40.3.2 Concrete struts with cracking diagonal or parallel to the strut

In this case, the compression stress-field forming a concrete strut can exhibit cracking that is diagonal or parallel to the direction of the compressions. Due to the state of stress and cracking in the concrete, its strength capacity in compression reduces considerably.

In a simplified manner, the strength capacity of the concrete can be defined in these situations in the following way:

- Where there are cracks parallel to the struts and a transverse reinforcement that is sufficiently anchored.

$$f_{lcd} = 0.70\, f_{cd}$$

- When the struts transmit compressions via cracks whose opening is controlled by sufficiently anchored transverse reinforcement (this is the case of beam webs subjected to shear stress).

$$f_{lcd} = 0.60\, f_{cd}$$

- When the compressed struts transfer compressions via wide cracks (this is the case of elements subjected to tension or T-beam flanges under tension).

$$f_{lcd} = 0.40\, f_{cd}$$

40.3.3 Concrete struts with compressed reinforcements

The reinforcement may be considered to make an effective contribution to the strength capacity of struts when it is located inside and parallel to the compression stress-field and there is sufficient transverse reinforcement to prevent these bars from buckling.

The maximum tension in the compressed steel may be considered to be:

$$\sigma_{sd,c} = f_{yd}$$

when compatibility conditions can be established to justify it, or

$$\sigma_{sd,c} = 400\ N/mm^2$$

when no explicit compatibility conditions can be established.
In this case, the strength capacity of the struts may be expressed as:

$$A_c\, f_{1cd} + A_{sc}\, \sigma_{sd,c}$$

In which A_{sc} is the area of the strut reinforcement.

40.3.4 Confined concrete struts

The strength capacity of struts can be increased if the concrete is suitably confined (figure 40.3.4). For static loads, the strength of the concrete may be increased by multiplying f_{1cd} by:

$$\left(1 + 1{,}5\, \alpha \omega_w\right)$$

in which:

ω_W Volumetric mechanical amount of confinement, defined by (see figure 40.3.4):

$$\omega_W = \frac{W_{sc}}{W_c}\frac{f_{yd}}{f_{cd}} = \frac{\sum A_{si} \cdot l_i}{A_{cc} \cdot s_t} \cdot \frac{f_{yd}}{f_{cd}}$$

Where:

- W_{sc} Volume of confining transverse reinforcement
- A_{si} Area of each of the transverse confining reinforcements.
- l_i Length of each of the transverse confining reinforcements.
- W_c Volume of confined concrete .
- A_{cc} Area of concrete enclosed by the confining steel.
- s_t Longitudinal spacing between the transverse confining reinforcements.

α Factor that takes account of the spacing between hoops, the type of concrete and the configuration of the confining reinforcement, whose value is: $\alpha = \alpha_c, \alpha_s\, \alpha_e$.

α_c Factor that takes account of the concrete strength, with a value of :

$\alpha_c = 1.0$ in the case of conventional concrete, with $f_{ck} \leq 50\ Nmm^2$.

$\alpha_c = 1.2 - \frac{f_{ck}}{250}$ in the case of high strength concrete, with $f_{ck} > 50\ Nmm^2$.

α_s Factor that takes account of the effect of the longitudinal spacing between hoops, with a value of:

$\alpha_s = \left(1 - \frac{s_t}{2b_c}\right) . \left(1 - \frac{s_t}{2h_c}\right)$ if the core is rectangular, with dimensions b_c,

h_c and is contained by longitudinally separated hoops s_t.

$\alpha_s = \left(1 - \frac{s_t}{2D}\right)^2$ if the area of the concrete confined by the steel has a circular cross-section of diameter D and is confined by hoops that are distance s_t apart.

$\alpha_s = \left(1 - \frac{s_t}{2D}\right)$ if the area of the concrete confined by the steel has a circular cross-section of diameter D and is contained by a spiral reinforcement with a pitch s_t.

α_e Factor that takes account of the effectiveness of the transverse reinforcement installed inside the confined area of the section, with a value of:

$$\alpha_e = 1 - \frac{\sum_{i=1}^{n} s_{1,i}^2}{6 \cdot A_{cc}}$$

in which the sum includes all the longitudinal reinforcements effectively tied by the transverse confining reinforcement and s_l is the spacing between the longitudinal reinforcements.

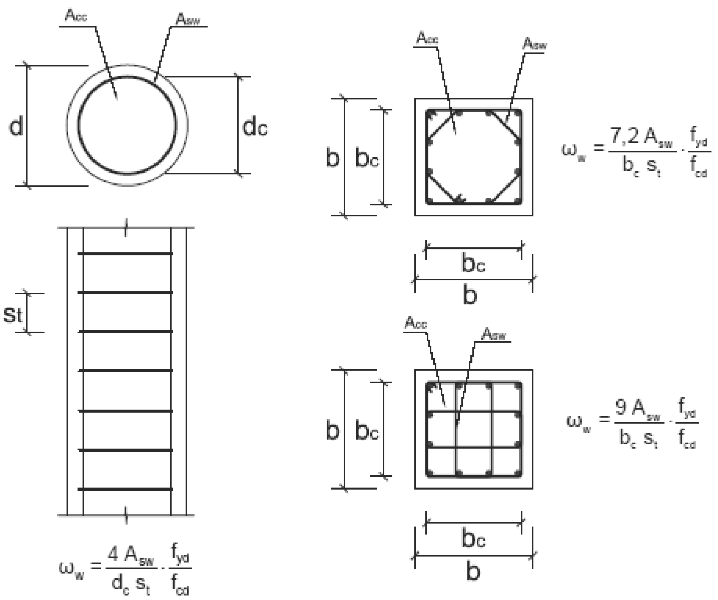
In the case of rectangular sections whose longitudinal laterally tied reinforcements are distance s_b apart along the width, and s_h along the height of the section, the factor α_e can be expressed as:

$$\alpha_e = 1 - \frac{\sum_{i=1}^{n} \left(s_{b,i}^2 + s_{h,i}^2\right)}{6 \cdot b_c \cdot h_c}$$

In the case of sections with circular hoops $\alpha_e = 1.0$.

In this case, the strength capacity of the struts can be expressed as:

$$A_{cc}\,(1 + 1.5\,\alpha_{\omega w})\,f_{lcd}$$



VOLUMETRIC MECHANICAL RATIO OF CONFINEMENT

Figure 40.3.4

40.3.5 Struts intersected by sheaths containing active reinforcements

If struts are intersected by sheaths of active reinforcements, whether bonded or unbonded, and if the sum of their diameters is more than b/6, with b being the total width of the strut, the widths to be considered in the verification of the strength capacity shall be reduced in accordance with the following factor:

$$b_0 = b - \eta\Sigma\phi$$

In which:

b_0 Width of the strut to be considered in the verification.
$\Sigma\phi$ Sum of the diameters of the sheaths, at the least favourable level.
η Coefficient which depends on the reinforcement's characteristics.
η = 0.5 in the case of sheaths with a bonded active reinforcement.
η = 1.0 in the case of sheaths with an unbonded active reinforcement.

40.4 Strength capacity of nodes

40.4.1 General

Nodes shall be designed, dimensioned and reinforced, so that all the acting forces are balanced, and the ties are suitably anchored.

The concrete at nodes may be subjected to multi- stress states and this particular feature shall be taken into consideration since it involves an increase or a reduction in its load carrying capacity.

The following aspects shall be verified at nodes:

- That the ties are properly anchored (Articles 69 and 70).
- That the maximum tension in the concrete does not exceed its maximum load carrying capacity.

40.4.2 Multi-compressed nodes

In nodes that only connect struts in compression (see figures 40.4.2.a and 40.4.2.b) a multi-compressed tension state normally obtains, which enables the compressive strength capacity of the concrete to be increased in accordance with the following factors:

$$f_{2cd} = f_{cd}$$

In the case of biaxial compression states, and

$$f_{3cd} = 3.30\, f_{cd}$$

in the case of triaxial compression states.

If these compression strength capacity values of the concrete of the node are considered, they shall take account of the induced transverse tensile stresses which usually require individual reinforcement.

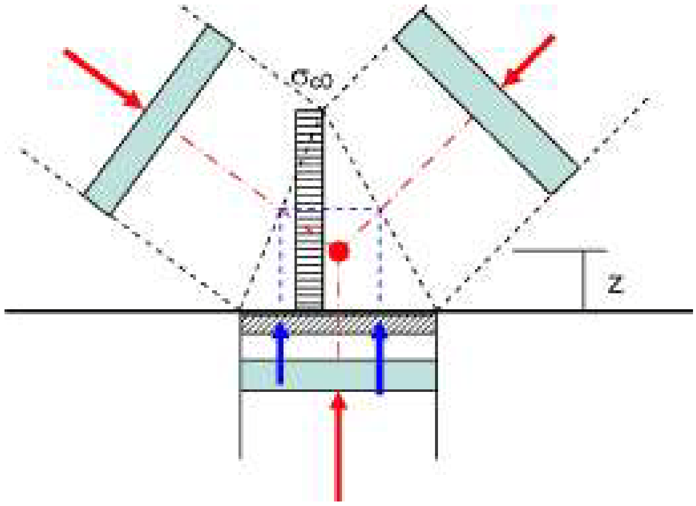


Figure 40.4.2.a

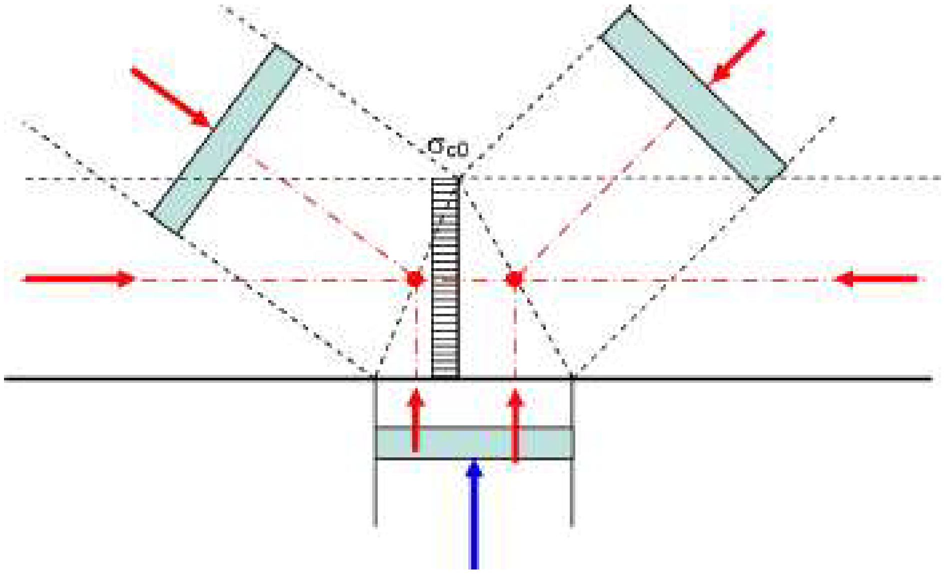


Figure 40.4.2.b

40.4.3 Nodes with anchored ties

The compressive strength capacity of this type of node is:

$$f_{2cd} = 0.70\, f_{cd}$$