STRENGTH CAPACITY OF STRUTS, TIES AND NODES

CHAPTER IX

Article 40 Strength capacity of struts, ties and nodes

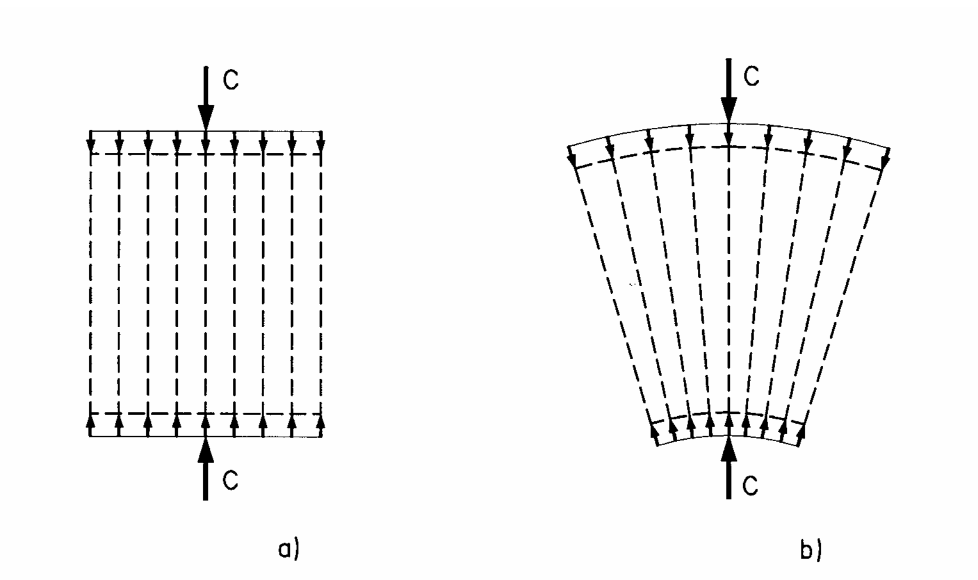
40.1 General

The strut-and-tie model forms a suitable procedure for explaining the behaviour of structural concrete elements, both in B and D regions (Article 24).

The elements in a strut-and-tie model are struts, ties and nodes.

The ties usually consist of reinforcing or pretressing steel

A strut may represent the resultant of either a parallel or a prismatic compression stress-field, as shown in figure 40.1.a, or fan-shaped compression stress-field, as shown in figure 40.1.b.



Figures 40.1.a and b

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

This article deals with the verification criteria for each of these elements at the Ultimate Limit State.

Although the criteria set out in this Chapter comprise Ultimate Limit State verifications~~,~~ which do not involve automatic verification of the Limit State for Cracking, certain limitations are defined here which, together with the general principles given in Article 24, lead to adequate control of cracking in practice.

COMMENTS

Examples of ties are transverse reinforcement of a beam web subjected to shear or the upper horizontal transverse reinforcement of a corbel.

Examples of struts are the compression stress-fields that are represented in the truss analogy of a beam web (fig. 40.1.c) or the compression stress-field that represent the load transfer of a corbel to the support (fig. 40.1.d).

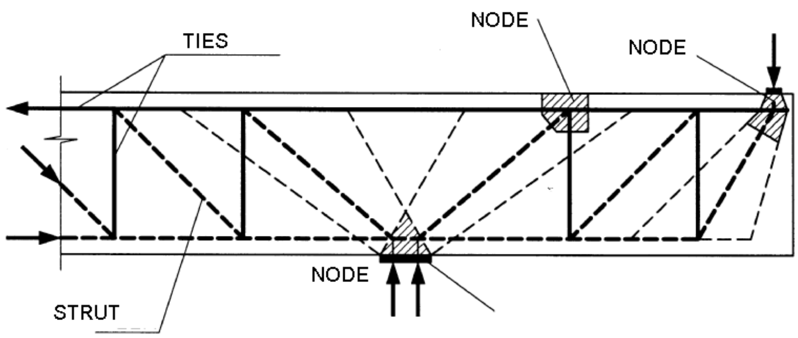


Figure 40.1.c

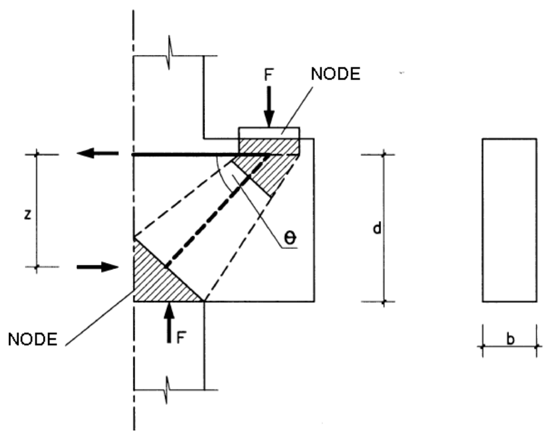


Figure 40.1.d

Example of node is the volume of concrete where several struts and support reaction intersect (figure 40.1.c), or where struts are deviated by a load (figure 40.1.d).

The criteria set out in Chapter X, Calculations in relation to Ultimate Limit States (Articles 41 to 47) for B regions are compatible with the verifications explained in this article. In a similar fashion, the criteria set out in Chapter XII, Structural elements (Articles 59 to 64), for various cases of D regions, are equally compatible with the verifications set out here.

40.2 Strength capacity of ties consisting of reinforcement bars.

At the Ultimate Limit State, it is supposed that the reinforcement attains the design stress

- For reinforcing steel: $\sigma_{sd} = f_{yd}$
- For prestressing steel : $\sigma_{pd} = f_{pd}$

When compatibility conditions are not explicitly studied, it will be necessary to limit the maximum strain in the ties at the Ultimate Limit State, and thus the stress in the reinforcement is indirectly limited at the Serviceability Limit State.

The strength capacity of a tie consisting of reinforcement bars may be expressed as follows:

$$A_s f_{yd} + A_p f_{pd}$$

where:

A_s The area of reinforcing steel
A_p The area of prestressing steel

COMMENTS

In the situation whereby the prestress is taken into account as an exterior equivalent load when obtaining the internal forces (Article 20), for the purpose of the tie strength capacity, only the stress increment due to the exterior loads should be considered.

$$\Delta \sigma_{pd} = f_{pd} - \sigma_{p,P_0}$$

where σ_{p,P_0} is the stress of the prestressing steel due to the characteristic value of the prestress at the moment when the tie verification is carried out. The tie strength capacity is then given by:

$$A_s f_{yd} + A_p (f_{pd} - \sigma_{p,P_0})$$

For suitable control of the stress under serviceability conditions and, consequently, of cracking, it is recommended that maximum deformation of the tie steel be limited to 2% when a detailed compatibility study is not performed. This involves limiting the total reinforcing steel stress to:

$$\sigma_{sd} \leq 400\ N/mm^2$$

and that of the prestressing steel to:

$$\Delta \sigma_{pd} = f_{pd} - \sigma_{p,P_0} \leq 400\ N/mm^2$$

This limitation is used, for example, to determine the shear strength capacity of the transverse reinforcement at the beam web or for the torsion transverse reinforcement.

40.3 Strength capacity of struts.

The capacity of a compressed strut is strongly influenced by the state of stresses and strains which are transverse to the compression stress-field and by the existing cracking.

40.3.1 Concrete struts in regions of 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:

$$f_{1cd} = 0{,}85\, f_{cd}$$

In addition to the diagrams defined in 39.5, a rectangular diagram may be used, such as the one shown in figure 40.3.1, the maximum stress being f_{1cd}, as defined below:

$$f_{1cd} = 0{,}85 \left(1 - \frac{f_{ck}}{250} \right) f_{cd} \text{, con } f_{ck} \text{ en } N/mm^2$$ with f_{ck} in N/mm²

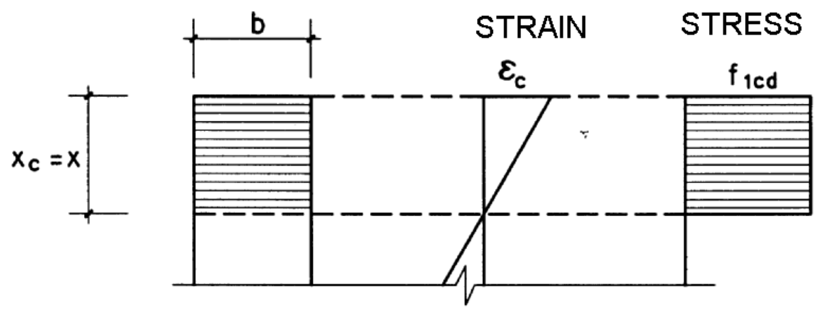


Figure 40.3.1

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

$$A_c\, f_{1cd}$$

where:

A_c Area of the compressed strut ($A_c = x\, b$)

COMMENTS

In some cases, those that the strut-and-tie model is used, the concrete is subjected to a stress gradient, without any explicit study of the deformation condition of the compressed strut. The explained criterion is useful in these situations to evaluate the strength capacity of a compressed strut in the non-cracked zone.

40.3.2 Concrete struts with diagonal or parallel cracking to the strut.

In this case, the compression stress-field that forms a concrete strut may show cracking that is diagonal or parallel to the direction of compression. Due to the state of stress and cracking in the concrete, the compressive strength capacity sharply falls.

The strength capacity of the concrete may then be defined in these cases in a simplified manner, in the following way:

- When there are cracks parallel to the struts, together with well-anchored transverse reinforcement:

$$f_{1cd} = 0{,}70\, f_{cd}$$

- When the struts transmit compression forces via the cracks, the width of which is controlled by well-anchored transverse reinforcement (this is true in the case of the web of beams subjected to shear).

$$f_{1cd} = 0{,}60\, f_{cd}$$

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

$$f_{1cd} = 0{,}40\, f_{cd}$$

COMMENTS

In order to evaluate the shear capacity that is conditioned by compression of the web concrete (44.2.3.1), the following is employed:

$$f_{1cd} = 0{,}60\, f_{cd}$$

In order to evaluate the shear at the interface that is conditioned by diagonal compression of the flanges (44.2.3.5), the following is employed:

- For compressed flanges

$$f_{1cd} = 0{,}60\, f_{cd}$$

- For flanges under tension

$$f_{1cd} = 0{,}40\, f_{cd}$$

In order to obtain the maximum punching strength (46.4), the following is employed:

$$f_{1cd} = 0{,}30\, f_{cd}$$

40.3.3 Concrete struts with reinforcement under compression~~.~~

The reinforcement can be considered as effectively contributing to the strength capacity of the struts when it is situated within and parallel to the compression stress-field and when there is sufficient transverse reinforcement to prevent these bars from buckling.

The maximum stress of the compressed steel may be taken as:

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

when it is possible to establish the compatibility conditions that justify it, or:

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

when explicit compatibility conditions are not established:

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

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

where A_{sc} is the strut reinforcement area .

COMMENTS

In this section, the maximum stress of the compressed steel, when the compatibility conditions are not explicitly studied, may be established by supposing that the failure of the compressed concrete is produced with a 2 ‰ deformation value.

40.3.4 Confined concrete struts

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

$$(1+1{,}6\,\alpha\,\omega_W)$$

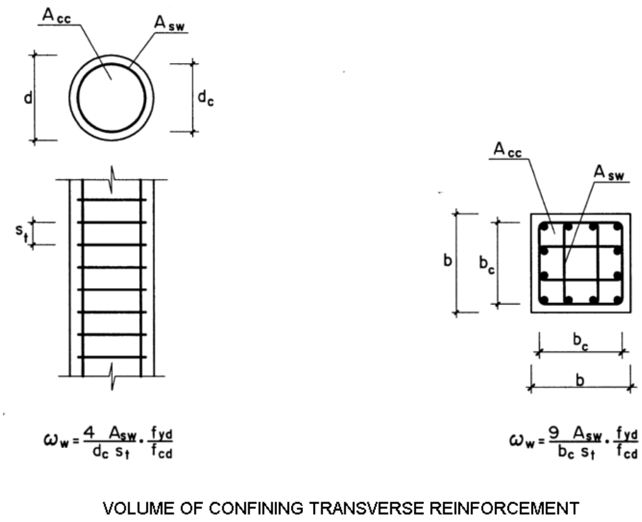


Figure 40.3.4.a

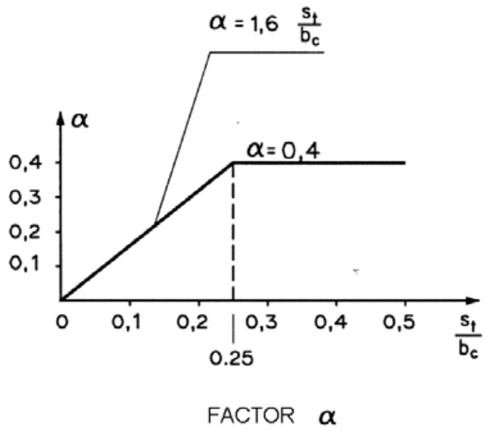


Figure 40.3.4.b

where:

α The factor defined in figure 40.3.4.b.

ω_W Volumetric mechanical reinforcement ratio, as defined by (see figure 40.3.4.a):

$$\omega_W = \frac{W_{sc}}{W_c}\frac{f_{yd}}{f_{cd}}$$

where:

W_{sc} is the volume of confining transverse reinforcement W_c Volume of confined concrete.

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

$$A_{cc}\,(\,1+1{,}6\,\alpha\,\omega_W\,)\,f_{1cd}$$

where:

A_{cc} Area of concrete enclosed by the confining steel.

COMMENTS

The bearing capacity of the confined concrete struts only refers to the area of concrete that is confined by the cross-section reinforcement, since the covering would have become loosened long before the confined concrete reached the attributed strength values.

40.3.5 Struts with interference from prestressing ducts

If the struts are crossed by either bonded or unbonded prestressing ducts and the sum of their diameters is greater than *b*/6, where *b* is the total width of the strut, the width to be considered in the bearing capacity verification should be reduced in accordance with the following criterion:

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

where:

b_0 Width of the strut that is to be considered in the verification.
$\Sigma\varnothing$ Sum of the sheath diameters, at the least favourable level.
η Coefficient that depends on the characteristics of the prestressing.
η=0,5 for sheaths with bonded prestressing steel.
η=1,0 for sheaths with unbonded prestressing steel.

40.4 Strength capacity of nodes~~.~~

40.4.1 General

Nodes shall be designed, dimensioned and reinforced in such a way that all the acting forces are balanced and the ties are properly anchored.

The concrete at the nodes may be subjected to multi-stress states, and this fact must also be taken into account since it implies either an increase or decrease in its strength capacity.

The following aspects of the nodes should be verified:

- Ties should be properly anchored (Articles 66 and 67).
- The maximum stress in the concrete should not exceed its maximum strength capacity.

COMMENTS

According to the specialised literature, the concrete bearing capacity at the nodes~~,~~ is not usually a conditioning factor since the required dimensions for the strut anchorage or the dimensions for supports or load introduction, determine the node dimensions.

40.4.2 Multi-compressed nodes.

In nodes that only connect struts under compression, as in the examples in figure 40.4.2, there is normally a multi-compressed state of stress that permits the compressive strength capacity of the concrete to increase in accordance with the following criteria:

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

for biaxial compressive states, and

$$f_{3cd} = 3,30\ f_{cd}$$

for triaxial compressive states.

When these values for the compressive strength capacity of concrete at the node are taken into account, consideration should also be given to the induced transverse stresses, which usually require specific reinforcement.

COMMENTS

The nodes indicated in the article correspond to, for example, to those used for the verification of local pressures (60.2.1). In this situation, the three dimensional behaviour depends on the relationship between the dimension of the loaded area(A_{c1}) and the area where the load is considered to be distributed (A_c), in accordance with the following expression:

$$f_{3cd} = \sqrt{\frac{A_c}{A_{c1}}}\ f_{cd} \leq 3,3\ f_{cd}$$

40.4.3 Nodes with anchored ties.

Nodes that are characteristic of this type are shown in figure 40.4.3. In this type of node the compressive strength capacity is:

$$f_{2cd} = 0,70\ f_{cd}$$

COMMENTS

This type of node corresponds to that of deep beam supports (62.4.2) or to that of the zone of applied loads on corbels (63.2.1.2).

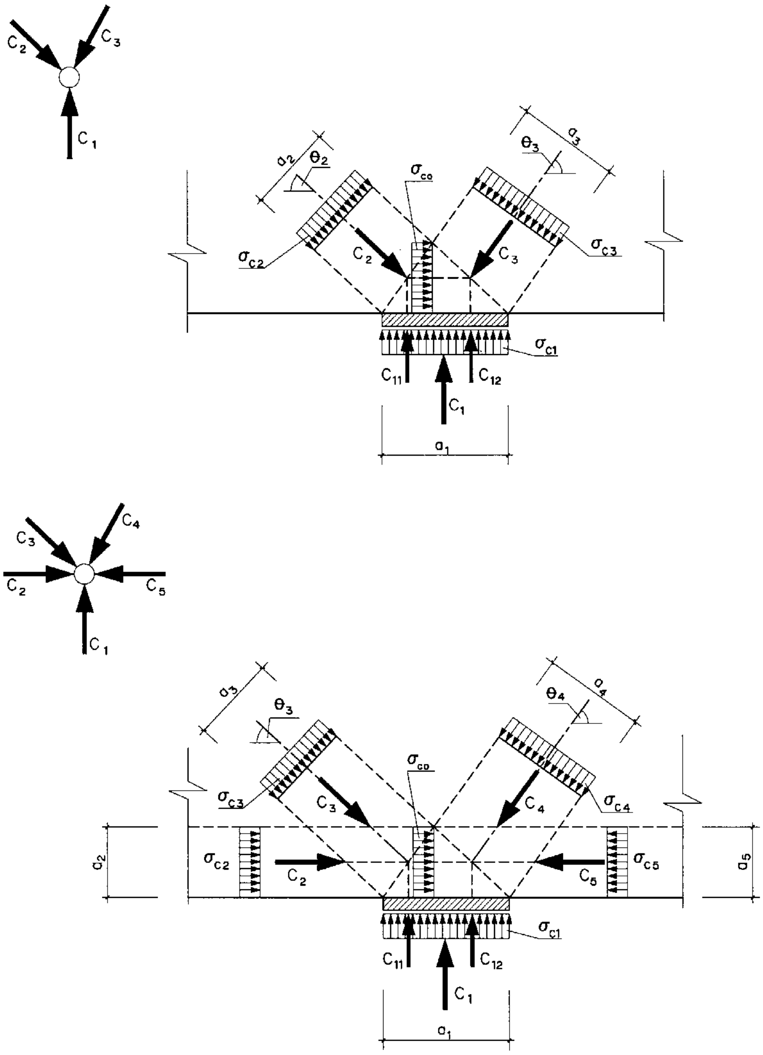


figure 40.4.2

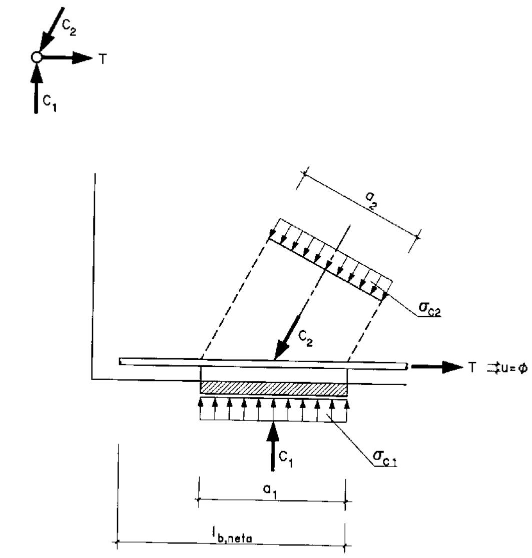


figure 40.4.3