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# Dimensioning of the Nodes and Development of Reinforcement

## Dimensionnement nodal et développement de l'armature

## Bemessung von Knoten und Entwicklung von Bewehrungen

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**SUMMARY**

This paper presents a proposal for the dimensioning process of nodal zones. Based on test results an efficiency factor for cylinder compressive strength from 20 to 80 MPa is proposed. In order to optimize the nodes, some geometrical constraints as well as an equation for the development length for straight bars under lateral pressure (CCT-, CTT-nodes), are also presented.

**RÉSUMÉ**

Cet article présente une proposition de dimensionnement des zones nodales. Basé sur des résultats d'essais, un facteur d'efficacité pour la résistance en compression de cylindres en béton de 20 à 80 MPa est présenté. On propose aussi quelques restricitions géométriques, ainsi qu'une équation pour les longueurs d'ancrage des barres droites soumises à effort tranchant, et ceci en vue de l'optimisation des nœuds.

**ZUSAMMENFASSUNG**

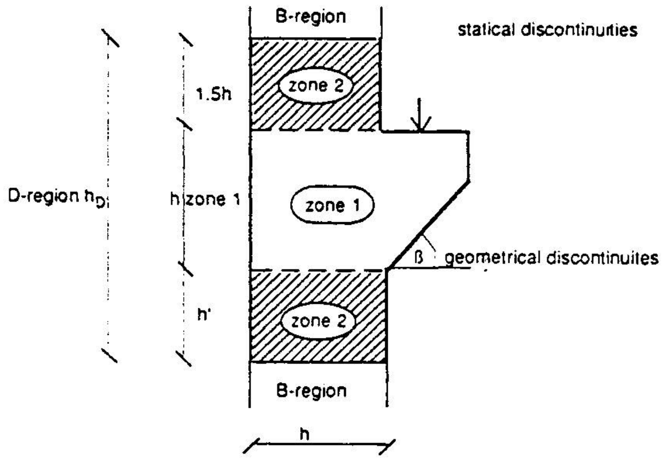
In dieser Veröffentlichung wird die Bemessung von Knotenbereichen aufgezeigt. Aufbauend auf Versuchen wird ein Vorschlag für die Wirksamkeit der Zylinderdruckfestigkeit von 20 bis 80 MPa vorgestellt. Sowohl geometrische Bedingungen als auch eine Gleichung für die Verankerungslänge von geraden Bewehrungsstäben mit Querpressung (CCT-, CTT-Knoten) sollen zur Optimierung von Knotenbereichen beitragen.

## 1. INTRODUCTION

Recent advances in the understanding of the behavior of concrete structures have resulted in more sophisticated methods of analysis. Computer based methods enable the elastic- and inelastic analysis of highly indeterminate and non-linear structures. For the majority of structures however it is unnecessary and inefficient to replicate the entire structure as a strut-and-tie-model (STM). Rather, it is more convenient and common practice to first carry out a general structural analysis, and then to subdivide the given structure into B-regions and D-regions [1]. It utilizes the well-known principle of Saint Venant which provides that local stresses may be assumed negligible at a distance $h_D$. For practical applications the following approaches as illustrated in Fig. 1 are suggested, and the total area of zone 2 + zone 1 + zone 2 is the effective D-region [2].

## 2. NODE BACKGROUND

D-regions usually contain either smeared or singular nodes. The singular nodes are more critical and need more attention. The following dimensioning and anchorage requirements must be applied to either smeared or singular nodes. The stress peaks in smeared nodes are less critical because a greater amount of surrounding concrete is normally available. The node of the STM represent the location of change of direction of internal forces. Evaluation of the nodal zones includes checking the nodal boundary stresses an determining reinforcement development requirements for nodes which contain tension ties.




h = height of the cross section

h' = 1.5 h cos ß

$h_D$ = h zone 1 + 1.5 h cosß + 1.5 h cosß (in general)

Fig. 1 Suggested subdivison of structure

### 2.1 Concrete efficiency factor

In general, the effective strength, $f_{ce}$, available for use in the struts is chosen as some fraction of the concrete compressive strength, $f_c$. It is given as the product of an efficiency factor, $\nu_e$ , and the 28 day cylinder compressive strength. The efficiency factor should take into account the following parameters:

- multiaxial state of stress
- disturbances from cracks
- disturbances from reinforcement
- friction forces
- aggregate interlock after cracking
- dowel forces
- time dependence

$$f_{ce} = f_c \cdot \nu_e \tag{1}$$

Various proposals for the efficiency factor have been presented. They are usually based on tests of continuous compression fields generated either in thin-web beams or thin shear panels, although some appear to be based largely on engineering judgement. Empirical relations for the concrete efficiency factor of concrete struts in beam webs as suggested by Nielsen et al. [3], Ramirez and Breen [4], Collins and Mitchell [5] are summarized below:

| | | | | |
|---|---|---|---|---|
| - Nielsen et al. [3]: | $\nu_e = 0.7 - f_c / 200$ | $f_c <$ | 60 MPa | (2) |
| - Ramirez, Breen [4]: | $\nu_e = 2.82 / \sqrt{f_c}$ | $\sigma_c <$ | $2.5\sqrt{f_c}$ MPa | (3) |
| - Collins, Mitchell [5]: | $\nu_e = 1 / (0.8 + 170\,\varepsilon_1)$ | | | (4) |
| | $\varepsilon_1 = \varepsilon_x + (\varepsilon_x + 0.002)\cot^2\theta_{cs}$ | $\varepsilon_x = 0.002$ | | |

Marti [6] suggested as a reasonable average value for the nodal zone $\nu_e = 0.6$. Schlaich et al. [1] propose values between 0.4 (extraordinary cracks) and 1.0 (undisturbed).

In many applications, substantial confining reinforcement may be present so as to greatly increase the efficiency factor for concrete in compression.
A total of 122 tests have been evaluated using the following approach [2] (see Fig. 2):

$$f_{ce3} = \nu_e f_c (A/A_b)^{0.5} + (A_{core}/A_b)\, f_{lat}\, (1 - s/d) \quad \text{[MPa]} \tag{5}$$

$$\nu_e = 0.5 + 1.25 / \sqrt{f_c} \quad [/] \tag{6}$$

$f_{ce3}$ = confined concrete strength [MPa]
d = equivalent diameter = side length of confined square core [mm]

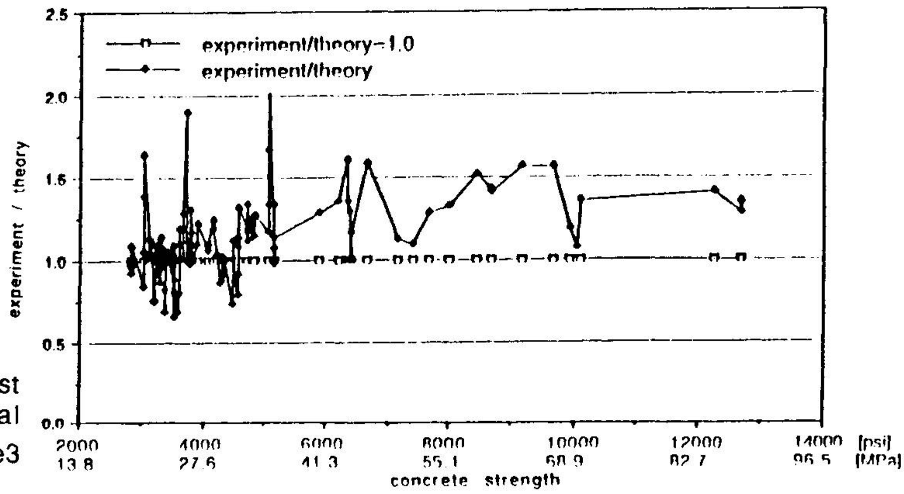



Fig. 2 Comparison of test results with theoretical approaches for predicting $f_{ce3}$

The proposed equation for the effective confinement strength is a generally conservative and safe approach. The 5%-fractile ($m-2\sigma = 1.124-2*0.238$) would be 0.65 which is also the minimum actual test value. The efficiency factor may be used with a concrete strength of up to 80 MPa.

## 2.3 Anchorage requirements in the nodal zone

All nodal zones are influenced by the tension tie anchorage details. If the resistance to applied tensile force is provided by bearing plates and does not rely appreciably upon bond stresses, then the tie actually provides a compression strut in terms of its action on the nodal zone (positive anchorage details). However, such positive anchorages are not necessarily required nor are they always desirable or practical construction alternatives for anchoring tensile ties. In CCT- and CTT-nodes the reinforcing bars are under lateral pressure from the compressive strut. When lateral pressure is applied, the bond strength increases approximately in proportion to the square root of the lateral pressure. In addition, the distance between the bearing plate and the reinforcing bar, "e", has an important effect as shown in the study by Lormanometee [7]. Various experimental studies were evaluated to develop a formulation for a possible reduction of the development length for a reinforcement bar under lateral pressure. Only tests in which failure occurred before the bars yielded were included. The lateral pressure acts similar to the action of transverse reinforcement. Based on a comprehensive review of a broad range of test results [2], the development length,"$l_d$", with transverse reinforcement,$A_{tr}$, and lateral pressure,$f_n$, can be expressed as follows:

$$l_d = \frac{d_b\{(3 f_s/[(f_c)^{0.5}]-50\}}{\{1.2+3c/d_b+(A_{tr}f_{yt})/(3.4\, s\, d_b)+[(f_n)^{0.5}(2.4-e^2/58000)]\}} \quad [\mathrm{mm}] \qquad (7)$$

$$(A_{tr}f_{yt})/(3.4\, s\, d_b) \leq 3.0 \qquad (8)$$

$$0 \leq [(f_n)^{0.5}\,(2.4-e^2/58000)] \leq 6.0 \qquad (9)$$

$d_b$ = bar diameter [mm]
$f_s$ = stress in the bar at the critical section [MPa]
$f_{yt}$ = yield strength [MPa]
$s$ = spacing [mm]

The proposed equation take the lateral pressure into account to a distance e = 350 mm.

## 3. CHECKING AND DIMENSIONING NODES

### 3.1 Checking and dimensioning CCC-, CCT- and CTT-nodes

The following equation is proposed for confined concrete strength:

a) Unconfined nodes without bearing plates:

$$\sigma \leq f_{ce}/\gamma \qquad (10)$$

$$f_{ce} = \nu_e\, f_c \leq 2.5 f_c \qquad (11)$$

b) Confined nodes

$$f_{ce3} = [(\nu_e\, f_c\, (A/A_b)^{0.5} + (A_{core}/A_b)\, f_{lat}\, (1 - s/d)^2)] \leq 2.5 f_c \qquad (12)$$

$\alpha$ = 4.0 for spiral confinement
= 2.0 for square confinement with longitudinal reinforcement
= 1.0 for square confinement without longitudinal reinforcement
$f_{lat}$ = lateral pressure = $2 f_y A_s / (d\, s)$ (13)

c) Unconfined nodes with bearing plates (e.g CCT- and CTT-nodes)
For CCT- and CTT- nodes the width of the strut can be found by considering geometrical constraints such as bearing plates and by assuming that the effective

width of the tensile tie is governed by the dimensions from the inside to the outside reinforcement layer.

$$f_{ce3} = \nu_e f_c (A/A_b)^{0.5} \leq 2.5 f_c \quad (14)$$

$$A/A_b \leq 4 \quad (15)$$

d) Triaxially confined nodes
The increase in strength due to three-dimensional states of compressive stresses may be taken into account if the simultaneously acting transverse compressive stresses are considered reliable. This may be particularly appropriate if supplementary transverse prestressing is applied.

$$f_{ce3} = 2.5 f_c$$

In order to optimize the CCT-node both stresses at the $C_1$ and $C_2$ faces should be the same (hydrostatic stress). Fig. 3 shows the geometric inter-relation of the strut width, $w_{1C}$, the tie width $w_{T3}$, and the angle $\phi_{cs}$. If the reinforcement is welded or bolted to the anchor plate, the stress configuration in the node is similar to that in a CCC-node.

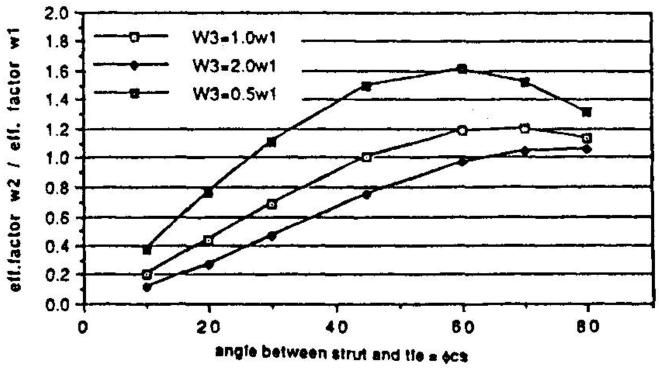



Fig. 3 Dependency of $\nu_e$ for CCT-node

When designing a CTT-node the reinforcement in both ties should yield at the same time. Since the compression strut,w2, is dependent on the tension tie widths,w1, and w3, the optimal concrete efficiency is given by the angle with the largest compression strut w2.

Tests by Bouadi [8] with CCT-nodes have shown that confining reinforcement has only a low effect (≈2%) on the failure load. Similarly, for the CTT-node (tests by Anderson [8]) in which the transverse reinforcement anchorage hooks were turned nearly parallel to the longitudinal bars (but not closed), the ultimate load decreased by only 4% compared with closed confining reinforcement.

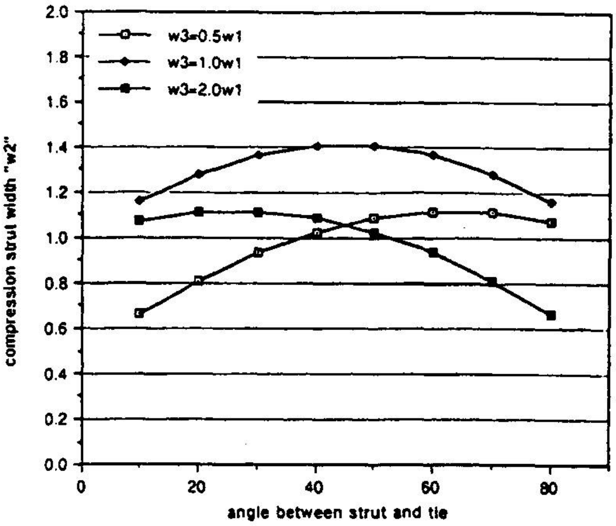



Fig. 3 Dependency of $\nu_e$ for CTT-node

By using vertically oriented hooks instead of long bars for the anchorage, the ultimate load decreased by 8% for CCT-nodes. This decrease is probably not significant given the other uncertainties in the design process. The advantage of hooks is that the required anchorage length can be minimized. Using a transverse U for the second tie in CTT-nodes provided lateral confinement, but prying action at the 90° bend can produce splitting cracks. In order to control splitting cracks of the end cover it is suggested that the longitudinal reinforcement be extended a short distance (≈s/2 or 50 mm) past the transverse reinforcement.

## 3.2 Checking and Dimensioning TTT - nodes

For TTT-nodes it must be evident that satisfactory behavior and adequate strength can be attained only by the efficient interaction of concrete and steel.

In details where the length available for end anchorage may be so short that only special devices can ensure the development of the required bar strength. For TTT-nodes the largest tensile tie should be anchored with looped - or hooked bars (Fig. 4). The stirrup spacing "s" must be so selected that the cover will not break away between two stirrups when the curved bar tends to straighten.

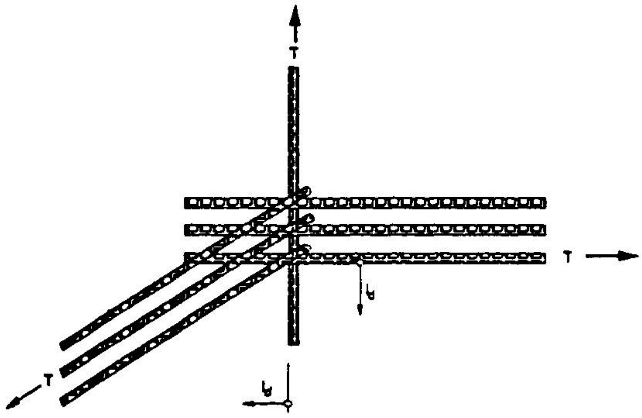


Fig. 4 TTT-node with looped bar

## 4. CONCLUSIONS

Some guidelines are given for the dimensioning process for the nodal zones. More research on this topic is needed as well as improved guidance for the serviceability control.
In order to satisfy the requirements of the theory of plasticity, a model must be in equilibrium under the applied loads. However, if the selected strut and- tie- model is to fully develop, the load carrying capacity of the strut- and- tie- elements and the rotational capacity of the nodes must not be exceeded before the ties yield. In addition the accepted standards for bar spacing, minimum reinforcement to control creep and thermal stresses should be applied.

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