CHAPTER 6 VERIFICATION OF STRUCTURAL SAFETY

6.3.3 Design shear capacity of linear members

(1) The design shear capacity of a member V_{vd} may be obtained using Eq. (6.3.2). When both bent longitudinal bars and stirrups are arranged as shear reinforcement, it should be ensured that the stirrups provided carry at least 50% of the shear force provided by shear reinforcement.

$$V_{yd} = V_{cd} + V_{sd} + V_{ped} \quad \textbf{(6.3.2)}$$

where V_{cd} **: design shear capacity of linear members without shear reinforcing steel, obtained using Eq. (6.3.3).**

$$V_{cd} = \beta_d \cdot \beta_p \cdot \beta_n \cdot f_{vcd} \cdot b_w \cdot d / \gamma_b \quad \textbf{(6.3.3)}$$

$$f_{vcd} = 0.20\sqrt[3]{f'cd} \ \textbf{(N/mm}^2\textbf{) where } f_{vcd} \le 0.72 \ \textbf{(N/mm}^2\textbf{)} \quad \textbf{(6.3.4)}$$

$\beta_d = \sqrt[4]{1/d}$ **(d : m)** **when** β_d **> 1.5,** β_d **is taken as 1.5.**

$\beta_p = \sqrt[3]{100 p_w}$ **when** β_p **> 1.5,** β_p **is taken as 1.5.**

$\beta_n = 1 + M_o / M_d \ (N'_d \ge 0)$ **when** β_n **> 2,** β_n **is taken as 2.**

$= 1 + 2M_o / M_d \ (N'_d \langle 0)$ **when** β_n **< 0,** β_n **is taken as 0.**

N'_d **: design axial compressive force**

M_d **: design flexural moment**

M_o **: flexural moment necessary to cancel stress due to axial force at extreme tension fiber corresponding to design flexural moment** M_d

b_w **: web width**

d **: effective depth**

$p_w = A_s / (b_w \cdot d)$

A_s **: area of tension reinforcement**

f'_{cd} **: design compressive strength of concrete (N/mm^2)**

γ_b **: 1.3 may be used in general**

V_{sd} **: design shear capacity of shear reinforcement, obtained using Eq. (6.3.5)**

$$V_{sd} = \left[A_w f_{wyd}(\sin\alpha_s + \cos\alpha_s)/S_s + A_{pw}\sigma_{pw}(\sin\alpha_p + \cos\alpha_p)/s_p\right]z/\gamma_b \quad \textbf{(6.3.5)}$$

A_w **: total area of shear reinforcement placed in** S_s

A_{pw} **: total area of prestressing steel expected to act as shear reinforcement placed in** S_p

σ_{pw} **: tensile stress in prestressing steel acting as shear reinforcement when shear reinforcing steel yields**

$\sigma_{pw} = \sigma_{wpe} + f_{wyd} \le f_{pyd}$

σ_{wpe} **: effective tensile stress in prestressing steel acting as shear**

reinforcement

f_{wyd} : **design yield strength of shear reinforcement, and should not exceed 400 N/mm². However, if the characteristic compressive strength of concrete (f'_{ck}) is 60 N/mm^2 or more, a value of up to 800 N/mm^2 may be used.**

f_{pyd} : **design yield strength of prestressing steel expected to act as shear reinforcement**

α_s : **angle between shear reinforcement and member axis**

α_p : **angle between prestressing steel acting as shear reinforcement and member axis**

S_s : **spacing of shear reinforcement**

S_p : **spacing of prestressing steel expected to act as shear reinforcement**

z : **distance from location of compressive stress resultant to centroid of tension steel; may generally be taken as d /1.15.**

γ_b : **member factor. May generally be taken as 1.10**

V_{ped} : **component of effective tensile force in longitudinal tendon parallel to the shear force, obtained using Eq. (6.3.6).**

$$V_{ped} = P_{ed} \cdot \sin\alpha_p / \gamma_b \qquad \textbf{(6.3.6)}$$

P_{ed} : **effective tensile force in longitudinal prestressing steel**

α_p : **angle between extreme compression fiber and member axis**

α_t : **angle between longitudinal prestressing steel and member axis**

γ_b : **1.10 in general**

(2) When linear members are supported directly, no further examination for V_{yd} may be required over a distance of one-half the total depth of members (h) from the face of the support. In this region, shear reinforcement not less than that required at the cross section located h /2 from the face of the support shall be provided. The depth at the face of the support may be used for members with varying depth, assuming that the haunch (whose slope does not exceed 1:3) is also effective in resisting shear forces.

Appropriate methods of design shall be used to estimate the design shear capacity in the neighborhood of supports, when planar members subjected to transverse shear are treated as linear members, and the provisions of Section 6.3.1(3) are used.

(3) The design diagonal compressive capacity V_{wcd} of web concrete in resisting applied shear forces may be calculated by Eq. (6.3.7).

$$V_{wcd} = f_{wcd} \cdot b_w \cdot d / \gamma_b \qquad \textbf{(6.3.7)}$$

where $f_{wcd} = 1.25\sqrt{f'_{cd}}$ **(N/mm^2), when** $f_{wcd} \leq 7.8$ **(N/mm^2)**

γ_b **: member factor. May generally be taken as 1.3**

(4) Web width of members

(i) In cases when the diameter of a duct in prestressed concrete members is equal to or greater than 1/8 of the width of the web, the width used in Eq. (6.3.3) shall be appropriately reduced (from the actual width, b_w). It is recommended that the web width may be reduced to ($b_w - 1/2\sum\varphi$), i.e. by an amount equal to one-half the sum of all the diameters of the ducts 'φ' spaced in the cross section.

(ii) For members with variable web width in the direction of member depth except for circular cross sections, the web width b_w shall be taken as the minimum width within the effective depth d. For members with several webs, the total width of webs shall be taken as b_w. For members with solid or hollow circular cross sections, the web width shall be defined as the side length of the square with the same area as solid circular cross section or the total width of webs of the square box having the same area as hollow circular cross section. In these cases, the area of longitudinal tensile steel A_s may be defined as the area of steel being arranged in 1/4 (90°) portion of the cross tensile section. The effective depth d may be taken as the distance from the edges of the squares or the square boxes at the compression side to the centroid of the steel section accounted as A_s, as shown in Fig.6.3.1.

These definitions of area for longitudinal tensile steel shall not be applied for the computation of flexural capacity.

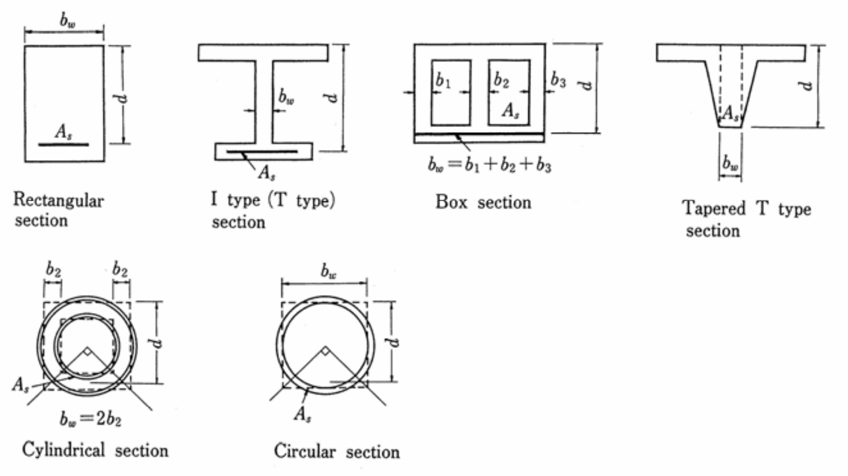

Fig. 6.3.1 Definitions of b_w and d concerning various shapes of cross sections

[Commentary] (1) The design shear capacity V_{yd} is basically the sum of the components carried by concrete V_{cd} and by shear reinforcement V_{sd}. The value of V_{sd} is calculated in accordance with the truss theory that assumes yielding of shear reinforcement and considers 45° compression diagonals. Consequently, V_{yd} gives the capacity corresponding to yielding of shear reinforcement. In reality, shear capacity may be considerably greater than V_{yd} if the amount of shear reinforcement is relatively small. However, no precise method to estimate the actual shear capacity is yet available, and therefore the present specification recommends use of Eq. (6.3.2) as a practical and conservative formula.

Eq. (6.3.3) is derived taking in to account the effect of concrete strength, member depth, reinforcement ratio and axial force on V_{cd}. Relationship between the shear strength by this equation and the characteristic compressive strength of concrete is shown in Fig. C6.3.2. The f'_{cd}

in Eq. (6.3.4) is the design compressive strength of concrete, obtained by dividing the characteristic compressive strength of concrete, f'_{ck}, by the material factor γ_c. The effects of the effective depth, ratio of axial reinforcement and axial forces are shown in Fig. C6.3.3 (a), (b) and (c). When the characteristic compressive strength of concrete exceeds 80 N/mm^2, there may not be a significant increase in V_{cd} even when the concrete compressive strength increases.

The Standard Specifications for Concrete Structures “Design” adopted in 1996, therefore, had placed an upper limit of 0.72 N/mm^2 for f'_{vcd}. In preparation for the change in the value of the material factor γ_c for concrete having a characteristic compressive strength of 60 N/mm^2 or more from 1.5 to 1.3, this upper limit was reviewed taking into consideration recent research results including the latest experiment data. As a result, although V_{cd} for concrete having a compressive strength of 60 N/mm^2 or more tended to level off, the review confirmed that safety can be ensured for all types of test specimens considered, even in the formula proposed by Niwa et al. that takes into account the effect of a/d, from which Eq. (6.3.3) was derived, by setting an upper limit of 0.72 for f'_{vcd} and using a material factor of 1.3. In view of the fact that Eq. (6.3.3) gives more conservative values than the Niwa formula because the former neglects the effect of a/d, use of Eq. (6.3.3) with an upper limit of f'_{vcd} of 0.72 and a member factor γ_b of 1.3 was permitted.

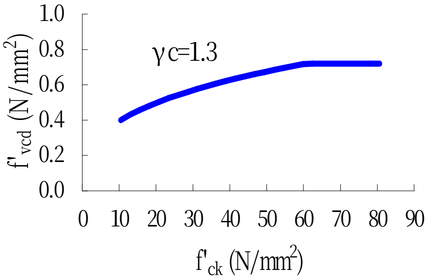

Fig.C6.3.2 Relationship between characteristic compressive strength of concrete f'_{ck} and f'_{vcd}

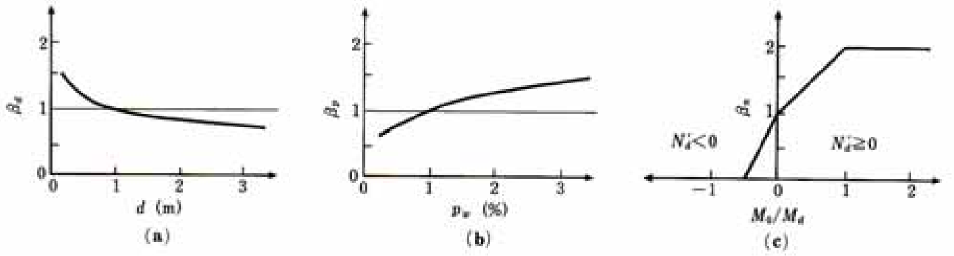

Fig. C6.3.3 Influencing factors on the shear capacity

Taking β_n as $(1+2M_o/M_u)$ may bring better applicability for the case of failure of members subjected to axial compression also, but for a conservative and safe estimate it may be assumed that $2M_o/M_u \approx M_o/M_d$, where M_d is the design flexural moment obtained based on the load for the ultimate limit state, and M_u is the design flexural capacity of members.

Only a few papers address the estimation of shear strength of members subjected to axial tension, and further research on the subject is required. Based on the experimental verification with previously reported test data, the value of β_n is found to be $1+2M_o/M_d$, where the definition of M_o is as shown in Fig. C6.3.4. For simplicity, the gross cross section of concrete may be considered to be effective when obtaining M_o.