doi.org/10.29295/2311-7257-2021-106-4-132-138
UDC 624.012.035

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RESEARCH OF METHODS FOR TRANSVERSE FORCE ACTION CALCULATION ON REINFORCED CONCRETE STRUCTURES

Different methods of transverse force (load) calculation are presented and compared depend on various building codes, such as EN, ACI, DBN etc. Transverse loading is a load applied vertically to the plane of the longitudinal axis of a configuration, such as a wind load. It causes the material to bend and rebound from its original position, with inner tensile and compressive straining associated with the change in curvature of the material. In problem under consideration, transverse loading encourages shear forces that cause shear deformation of a material and increase its slanting deflection. When a transverse load is applied on a reinforced concrete beam, it deforms and tensions develop within it. From the comparison of the calculation results, it is determined that the results of the theoretical values of the strength of the bending element by the transverse force, evaluated by various variants of ACI 318-14, are the closest.
Keywords: building codes, transverse force, reinforced concrete, contribution, calculation.

Introduction. To date, in Ukraine, the main provisions for the calculation of concrete and reinforced concrete structures are determined by national standards [1], based on EN 1992-1-1-2004 [2]. According to these standards, when calculating transverse force effect on bending reinforced concrete elements, the contribution of concrete to the resistance to the action of transverse force is taken into account only in the absence of transverse reinforcement, and if present, the bearing capacity of the section is determined only by the resistance of this reinforcement, with disregard of concrete resistance.

Such disregard of the contribution of concrete to the resistance to the action of transverse force often contradicts the methods of calculation adopted by many foreign standards, as well as the experience of designing real structures and experimental data.

In the overwhelming majority of modern standards, the "truss" model of calculation for transverse force is adopted, although it cannot be considered perfect and needs to be improved.

Purpose of the research - determination of the most rational way of determining the carrying capacity of bending elements on the action of transverse forces.

Analysis of previous research. In the model adopted by the American standards of the ACI 318-14 Code [3], the model assumes that the contribution of concrete to shear resistance (V_c) is defined as a value proportional to the square of the cylindrical concrete strength, and the compressed part of concrete is considered a kind of keyed connection. The angle of inclination of the diagonal crack at the destruction of the element is fixed at 45°.

Such standards do not take into account such factors as the opening width and depth of the crack, the axial stiffness of the element, the roughness of the concrete in the crack, the effect of the uneven distribution of the longitudinal force over the section of the element (especially for T-sections). Therefore, this "basic" calculation method is constantly being improved and modified.

Main material. So, with the "basic" method [3], the contribution of concrete to the bearing capacity of a bending element by the transverse force (in the absence of pre-stress and axial force):

$$V_c = 2\lambda\sqrt{f_c^I}b_w d \,. \tag{1}$$

In the modified version (method detail) the contribution of concrete is taken as the smaller of the values [4]:

$$V_c = \lambda(1.9\sqrt{f_c^I} + 2500\rho\frac{Vd}{M})b_w d; \tag{2}$$

$$V_c = \lambda(1.9\sqrt{f_c^I} + 2500\rho)b_w d; \tag{3}$$

$$V_c = 3.5\lambda\sqrt{f_c^I}b_w d. \tag{4}$$

where λ = 1 for heavy concrete, when converting V_c into kN, accepted as λ = 0.0069; f_c^I – is a design concrete compressive strength (psi); $\rho = A_s/b_w d$ is the longitudinal reinforcement coefficient; b_w – is the minimum wall thickness of the beam (inch); d – is the working height of the beam (inch).

Further modernization of the "basic" model is proposed in [5], where the contribution of concrete to shear resistance is determined by the formula:

$$V_c = 2\sqrt{f_c^I}\frac{2.25}{(1 + 1500\varepsilon_x)}\frac{50}{(38 + s_x)}b_w d \tag{5}$$

Here, it is shown that the shear resistance of concrete depends on the average strain of concrete ε_x and on the transverse reinforcement spacing s_x (deformability effect).

The value of ε_x is determined by the formula:

$$\varepsilon_x = \frac{M/_{0.9d} + V + 0.5N - A_p f_{se}}{2(A_s E_s + A_p E_p)}, \tag{6}$$

where M, V – is the bending moment and shear force in the considered section, respectively; N - is the longitudinal force; A_s, A_p - is the cross-sectional area of the longitudinal non-stressed and pre-stressed reinforcement, respectively; $A_p f_{se}$ - is the prestressing force; E_s, E_p - is the modulus of deformations of non-stressed and pre-stressed reinforcement, respectively.

If the stresses in the longitudinal reinforcement do not exceed 60 ksi (414 MPa), then for the most bending elements, it is assumed as follows:

$$V_c = \frac{100}{38 + s_x}\sqrt{f_c^I}b_w d. \tag{7}$$

And the transverse reinforcement bay can be taken as constant, recommended as s_x = 12 inch = 30.5 cm.

For elements with transverse reinforcement, the angle of inclination of the crack is determined by the formula:

$$\theta = 29^{\circ} + 7000\varepsilon_x, \tag{8}$$

where ε_x is determined by the formula (6).

The contribution of transverse reinforcement to the shear resistance:

$$V_s = 0.9A_v f_{yt} d \cdot ctg\theta / s_x, \tag{9}$$

where A_v – is the cross-sectional area of transverse reinforcement; f_{yt} - is the design resistance of transverse reinforcement.

In the methodology based on the Multi-Action Model [6], a solution is proposed where the contribution of concrete to shear resistance is specified depending on the size of the compressed section flange, and the fracture model is characterized by two branches: the main diagonal *a-b* extending from the bottom edge of the beam to neutral axis, and developing along the second branch *b-c* in the compressed zone from a different angle, where the concrete is working for tearing (Fig. 1).

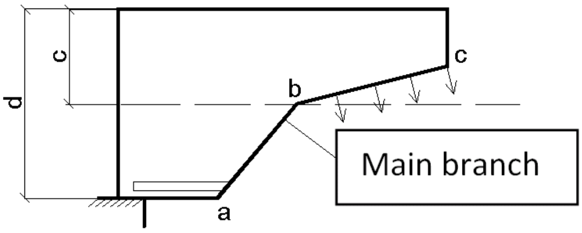

Fig. 1. The nature of the destruction of the element from the action of transverse force

The bearing capacity of the element $V_u = V_c + V_s$ with the contribution of concrete:

$$V_c = 6\lambda\xi \frac{c}{d}\sqrt{f_c^I}\, b_{w\,eff}\, d, \tag{10}$$

where $b_{w\,eff}$ – is the effective width of the compression flange of the T-section beam; ξ – is the factor of size and flexibility, determined by the formula:

$$\xi = \frac{2}{\sqrt{1 + {d_0}/{s}}}\left(\frac{d}{a}\right)^{0.2} \tag{11}$$

where $d_0 = d \leq 4$ inch; s - is the bay of transverse reinforcement; $a = M/V$, for beams with length of L with $L/d \leq 17.5$, it is accepted $d/a = 1/3.5$; c - is the height of the compressed zone of concrete.

The value of c/d can be obtained from the analysis of cracking with pure bending.

Also, in practical calculations one can take c/d equal to:

- 0.2 - for weakly reinforced elements;
- 0.25 - with average reinforcement;
- 0.35 - with highly reinforced elements.

The angle of inclination of the crack along the main branch is determined by:

$$tg\theta = 0.85d\,/\,(d - c) \leq 2.5. \tag{12}$$

The contribution of transverse reinforcement:

$$V_s = 1.2\, A_v\, f_{yt}\,/\,s. \tag{13}$$

In [7], a certain unified approach is proposed for solving the strength of bending elements by shear.

The bearing capacity of the section $V_u = V_c + V_s$ with the contribution of concrete:

$$V_c = 5\lambda\sqrt{f_c^I}\, b_w c \gamma_d; \tag{14}$$

$$c = d\sqrt{(\rho n)^2 + 2\rho n} - \rho n; \tag{15}$$

$$\rho = A_s/b_w d\ ;\ n = E_s\,/\,E_c; \tag{16}$$

$$\gamma_d = \frac{1.4}{\sqrt{1 + {d}/{d_0}}}. \tag{17}$$

In the formula (17) it is accepted $d_0 = 100$ inch, if $A_v \geq A_{v\,min}$ and $\gamma_d = 1$ if $d < 10$ inch.

The contribution of transverse reinforcement:

$$V_s = A_v\, f_{yt}\, d\, /\, s. \quad (18)$$

The ultimate strength for shear is limited by the conditions:

$$V_u \leq 0.75(V_c + 8\sqrt{f_c^I}\, b_w d);\ V_u \leq 4V_c\ . \quad (19)$$

The proposed method is applicable to conventional and prestressed elements, with and without transverse reinforcement, to polymer concrete and polymer elements.

The authors of [8] accept the contribution of concrete to shear resistance as a quantity proportional to the height of the intact compressed zone of concrete c and the ratio of span-shear to bending strength raised to the power of of 0.7 (distance concept). This concept is adopted by the Joint ACI - ASSE Committee 446 Fracture Mechanics of Concrete.

The bearing capacity of the cross section on the transverse force $V_u = V_c + V_s$,

$$V_c = 17\lambda \left(\frac{V}{M}\right)^{0.7} \sqrt{f_c^I}\, b_w c \frac{1}{\sqrt{1 + {}^{h}/_{11.8}}} \quad (20)$$

where c - is determined by (15); h - is the height of the element.

The contribution of transverse reinforcement V_s is determined by (18).

In [9], the mechanism of destruction under the action of transverse force is also considered two-legged (Fig. 1).

The value of the contribution of concrete to the bearing capacity of the transverse force:

$$V_c = K_s\, f_t\, b_w\, c\, ctg\theta. \quad (21)$$

where c – is the height of the compressed zone of concrete, defined by (15); K_s - is the coefficient depending on the height of the element:

$$K_s = \left(\frac{12}{d}\right)^{0.25} \leq 1.1 \quad (d \text{ – by inch}), \quad (22)$$

where f_t – is the calculated tensile resistance strength of concrete taken to be:

$$f_t = 2.2\lambda\sqrt{f_c^I} \quad (f_c^I \text{ – in psi}), \quad (23)$$

$$\text{ctg}\ \theta = \frac{\sqrt{f_t(f_t + \sigma_{ct})}}{f_t}, \quad (24)$$

where σ_{ct} – is the average normal stress from the bending moment.

The contribution of transverse reinforcement is determined by (18).

A refined method for determining the contribution of V_c to the strength of an element for shear is proposed in [10] (Germany).

The authors believe that the contribution of concrete to the bearing capacity of an element by shear is different in the presence of transverse reinforcement (V_c) and in its absence (V_{ct}).

In the presence of transverse reinforcement:

$$V_c = 0.066\, f_{cwu}\, b_w\, z, \quad (25)$$

where the design resistance of the concrete of the compressed zone when working for the shear force is taken as:

$$f_{cwu} = 0.7\, f_c^I. \quad (26)$$

The angle θ is limited by the condition:

$$1 \leq ctg\theta = \frac{ctg\beta_2}{\left(1 - {}^{V_c}/_{V_u}\right)} \leq 3, \quad (27)$$

where $z = 0.9d$.

$$V_u = V_c + V_s \; ; \; V_{u\,max} = b_w z\, f_{cwu} \,/\, (ctg\theta + tg\theta) \; ; \qquad (28)$$

$$ctg\,\beta_2 = 1.2 - 1.4\sigma_c / f_c^I \; , \qquad (29)$$

where $\sigma_c = N/A_c$ is the average stresses in the beam from the longitudinal force N or from the prestress.

The contribution of transverse reinforcement:

$$V_s = A_v\, f_{yt}\, z\, ctg\theta \,/\, s. \qquad (30)$$

In the absence of transverse reinforcement the bearing capacity of concrete:

$$V_{ct} = (71\sqrt[3]{\frac{\rho f_c^I}{d}} - 0.23\sigma_c) b_w d. \qquad (31)$$

In the absence of longitudinal force:

$$V_{ct} = 71\sqrt[3]{\frac{\rho f_c^I}{d}}\, b_w d. \qquad (32)$$

The authors of [11] consider that when designing bending elements according to the standards [1] for normal operating conditions of reinforced concrete structures (without force majeure situations), it is possible to determine the bearing capacity of the bending elements by shear by the sum of two components - concrete resistance ($V_{Rd,c}$) and the resistance of transverse reinforcement ($V_{Rd,s}$), which is confirmed by other authors, as well as field experiments.

Results. Table 1 below shows the results of calculations of the strength of bending element without prestressing by the action of transverse force according to the described methods.

A reinforced concrete beam with a span of L = 6 m, made of concrete of class C25/30, reinforced with longitudinal reinforcement 2Ø25A400 (A_s = 9.82 cm^2), transverse reinforcement 2Ø8 A400 ($A_{sw} = A_v$ = 1.01 cm^2) with bay $s = s_x$ = 30 cm = 12 inch, is considered. Design conditions M = 120 kNm; V_{Ed} = 80 kN.

Design characteristics: $f_{ck,cub}$ = 30 MPa; $f_{ck,\,cyl}$ = 25 MPa = 3625 psi; $f_{cd} = f_c^I$ = 17 MPa = 2465 psi. Working section height: d = 46 cm = 18.11 inch. Section width $b = b_w$ = 20 cm = 7.87 inch. The results of the calculations are given in Table.1.

Table 1 - The results of calculations of the strength of a bending element without prestressing by the action of transverse force

Calculation method	Concrete strength V_c, kN	Strength of transverse reinforcement V_s, kN	Bearing capacity $V_u=V_c+V_s$, kN
DBN V.2.6-98:2009 [1], EN 1992-1-1 (Eurocode 2) [2]	-	119.2	119.2
ACI 318-14 ("basic") [3]	97.7	67.8	165.5
ACI 318-14 [4] (updated, USA)	101.7	67.8	169.5
ACI 318-14 [5] (modification, Canada)	107.5	62.9	170.4
Multi-Action Model [6] (Spain)	98.6	52.1	150.7
ACI 318-14 [7] (Unified approach, US)	114.0	43.4	157.4
"Spacing model" [8] (US, Taiwan)	83.8	43.4	127.2
Unified solution [9] (South Korea)	71.4	43.4	114.8
ACI 318-14 [10] (modification, Germany)	100.8	93.6	194.4
	89.7	-	89.7
DBN B.2.6-98:2009, (practical calculation) [11]	67.2	99.3	166.5

The authors do not make comparisons with the results of calculations under the standards of Russia (SNiP 52-01-2003 and SP 63.13330-2012) and Belarus (SNB 5.03.01-02). Such comparisons were made earlier [12].

Conclusions. From the comparison of the calculation results, it can be seen that the results of the theoretical values of the strength of the bending element by the transverse force, determined by various modifications of ACI 318-14, are the closest.

In the proposed practical calculation [11], with a total bearing capacity close enough to the results obtained from modifications of the ACI 318-14 standards, the contribution of individual components (V_c and V_s) differs upward the bearing capacity of transverse reinforcement and downwards the contribution of concrete.

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Шмуклер В.С., Набока А.В., Фірсов П.М. ДОСЛІДЖЕННЯ МЕТОДІВ РОЗРАХУНКУ ДІЇ ПОПЕРЕЧНИХ СИЛ НА ЗАЛІЗОБЕТОННІ КОНСТРУКЦІЇ. В даній статті представлене порівняння різних методів розрахунку поперечної сили (навантаження), які залежать від конкретних будівельних норм, наприклад, EN, ACI, ДБН тощо. Поперечне навантаження - це навантаження, прикладене вертикально до площини поздовжньої осі конструкції, наприклад, вітрове навантаження. Це змушує матеріал згинатися і зумовлює вертикальні і горизонтальні переміщення від його початкового положення, при цьому внутрішні деформації розтягу та стиску пов’язані зі зміною кривини матеріалу. У задачі, що розглядається, поперечне навантаження сприяє зусиллям зсуву, які викликають деформацію зсуву матеріалу та збільшують його прогин. При дії поперечного навантаження на залізобетонну балку вона деформується і розтягується. За результатами порівняння розрахунків встановлено, що результати теоретичних значень міцності згинального елемента за поперечною силою, оцінювані за різноманітними варіантами норм ACI 318-14, є найбільш близькими.

Ключові слова: будівельні норми, поперечна сила, залізобетон, розподіл, розрахунок.