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Research paper

Shear resistance of reinforced concrete elements according to Model Code 2020

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Abstract: Evolution of methods for determining shear resistance in reinforced concrete structural elements led to the approach proposed in the new Model Code 2020. It is based on the strut-and-tie model and allows for verification on three levels of approximation. In this paper, the new approach is presented and illustrated for three levels of approximation, I, IIa, and IIb, and then compared with Eurocode 2. For the calculation of the design shear resistance according to Eurocode 2, the inclination of the concrete compression strut cot θ was assumed to be the same as for Model Code 2020. The prediction of shear resistance was studied on a rectangular cross-section, assuming two concrete classes and two types of vertical stirrups with varying spacing. To facilitate the interpretation of the results, they were scaled using coefficients and plotted. The most severe criteria for the support zone are obtained using Eurocode 2 and Model Code 2020, level of approximation I. The detailed analysis using Model Code 2020 level of approximation IIb leads to the smallest amount of the shear reinforcement, because it accounts for the participation of concrete in the design shear resistance. More advanced design approaches yield economic benefits but require more expensive designs.

Keywords: shear resistance, reinforced concrete, Model Code 2020, Eurocode 2, support zone

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1. Introduction

Mechanism of failure due to shear in reinforced concrete structures is a complex problem, resulting from diagonal cracking, partial rotation of the element, aggregate interlock and unlock at the tensile reinforcement, and possible cracking at that level [1, 2]. The evolution of models for the idealization of laboratory-observed phenomena, as well as methods for determining the shear capacity of reinforced concrete elements, led to the approach proposed in the pre-standard Model Code 2020 [3].

The first truss model for shear design, developed by Mörsh [4] almost a hundred years ago, established the basis for further studies in this field [5–15] and for the development of the strut-and-tie method for the design of reinforced concrete structures [16]. The truss consists of top and bottom chords formed correspondingly by concrete in compression and reinforcement in tension, compressed concrete struts formed between cracks, and transverse reinforcement in tension. The arrangement of struts and ties that reflects load-carrying actions is derived from the analysis of suitable stress fields. The basic elements for stress fields and the strut-and-tie model for the end region of a beam are presented in Fig. 1.

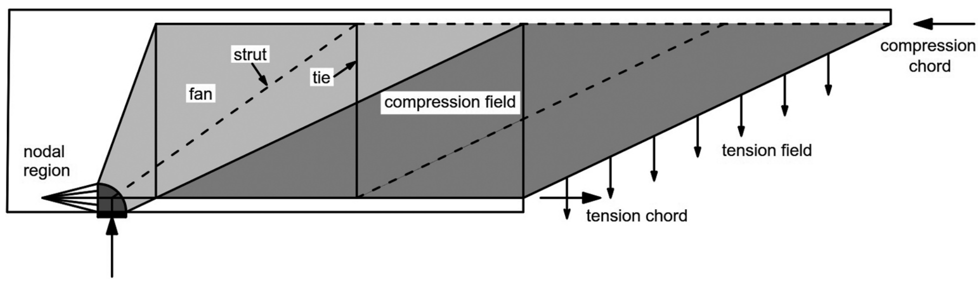

Fig. 1. Basic elements for stress fields and the strut and tie model

The load-bearing capacity can be easily evaluated based on equilibrium and yield conditions, considering the rigid-plastic response of the materials. For more refined results, advanced verifications are possible. The strength reduction factor, which accounts for the decrease in concrete compressive strength due to cracking rather than conservatively assuming it is constant, may be associated with the cracking state of the concrete and calculated precisely. The Variable Angle Truss models (VAT) assume shear resistance as a function of the amount of shear reinforcement [17]. Regime I corresponds to a low amount of shear reinforcement and a minimum angle of inclination of the concrete strut; regime II is related to simultaneous damage of the concrete strut under compression and yielding of the shear reinforcement; and regime III represents the case of concrete cracking at an angle of 45° without yielding of the shear reinforcement. Another approach is the Modified Truss Analogy (MTA), which is based on similar principles but accounts for the contributions of concrete and shear reinforcement in both compression and tension. Generally, more advanced methods result in less shear reinforcement but are more complex and require greater design experience.

The slender and squat members behave differently. The models appropriate for squat members are not sufficiently safe for slender members. The variable- angle truss models, appropriate for slender members, are found to be too conservative for squat members. The reasoning behind this is a more favourable cracking state, and the fact that in thicker cross-sections, concrete struts can form more easily without the need to be suspended by shear reinforcement. Similarly, excessively conservative results are observed for cases with concentrated forces applied at the top of the element near the support, due to a direct strut that develops between the point of application of the force and the support. Thus, formulas for empirical corrections to shear resistance are necessary.

Approaches developed for the Model Code 2020 and the 2nd generation of Eurocode 2 provide accurate predictions of shear resistance with a smooth transition between slender and squat members. The Applied Stress Field with Concentrated Struts (CSSF) method is a simplification of the Elastic-Plastic Stress Fields (EPSF) method, which combines a direct inclined strut and two fan regions. First Level of Approximation (LoA I) is intended for the simple design of new structures, assuming a constant efficiency factor ($\nu = 0.5$) and limiting the inclination of struts as for slender members. The second Level of Approximation (LoA II) can be used for detailed design and assessment of existing structures. It allows for the calculation of the tensile strain in shear reinforcement, accounting for compatibility of deformations, the point efficiency factor (ν) based on strain state, and the inclination of struts (θ) without limitations. The third Level of Approximation (LoA III) is based on the Stress Field with the Spread Strut method (SSSF), which is also a simplification of the Elastic- Plastic Stress Fields method (EPSF). It considers shear reinforcement and horizontal web reinforcement to account for the spreading of the direct strut, while the efficiency factor remains dependent on deformation compatibility, as in LoA II [17].

In this paper, the differences in predicting shear resistance using the levels of approximation from Model Code 2020 [3] and Eurocode 2 [18] were analysed. Calculations were performed for a rectangular cross-section, including two concrete classes and two types of shear reinforcement with variable spacing. Then, the results were normalized, plotted, and discussed.

2. Shear resistance according to Model Code 2020

2.1. General assumptions

The shear verification of a web or of a slab should be performed at control sections at a distance d from the face of the support, discontinuity of geometry, or applied force, assuring that the design shear force V_{Ed} is smaller than the design shear resistance V_{Rd}. In special cases, other control sections may be required. The contribution of point loads applied close to the supports may be reduced by the factors:

$$k_{\mathrm{dir}} = \begin{cases} \dfrac{a_v}{2d} \le \dfrac{1}{2} & \text{for } d \le a_v \le 2d \\ 0.5 & \text{for } a_v \le d \end{cases} \tag{2.1}$$

where: a_v – the distance of the applied force from the face of the support, d – the effective depth of the cross-section in flexure.

The effective shear depth for members containing ordinary and prestressing steel is:

$$z_v = \frac{z_s^2 A_s + z_p^2 A_p}{z_s A_s + z_p A_p} \geq 0.72h \tag{2.2}$$

where: z_s, z_p – distances between the centreline of the compressive chord and the ordinary or prestressing reinforcement correspondingly, A_s, A_p – area of the ordinary and prestressing reinforcement correspondingly, h – height of the cross-section.

The longitudinal strain calculated at the mid-depth of the effective shear depth is defined by the formula (2.3) and for prestressed concrete structures with bonded tendons by (2.4):

$$\varepsilon_x = \frac{1}{2E_s A_s}\left(\frac{M_{Ed}}{z_v} + \frac{V_{Ed}}{2}\cot\theta + N_{Ed}\left(\frac{1}{2} - \frac{\Delta e}{z_v}\right)\right) \geq 0 \tag{2.3}$$

$$\varepsilon_x = \frac{\dfrac{M_{Ed}}{z_v} + \dfrac{V_{Ed}}{2}\cot\theta + N_{Ed}\left(\dfrac{z_p - e_p}{z_v}\right)}{2\left(\dfrac{z_s}{z_v}E_s A_s + \dfrac{z_s}{z_v}E_p A_p\right)} \geq 0 \tag{2.4}$$

where: E_s, E_p – modulus of elasticity of ordinary steel and prestressing steel, z_v – effective shear depth, M_{Ed} – the design moment, V_{Ed} – the design shear force, N_{Ed} – the design axial force, Δe – the eccentricity, θ – inclination of concrete strut, e_p – eccentricity of prestressing tendons.

The inclination of the concrete compressive strut can be freely selected within the limits:

$$1 \leq \cot\theta \leq \cot\theta_{\min} \tag{2.5}$$

Loads carried directly to a support through a strut or an arch action, according to levels approximation I and II, are presented in Figure 2.

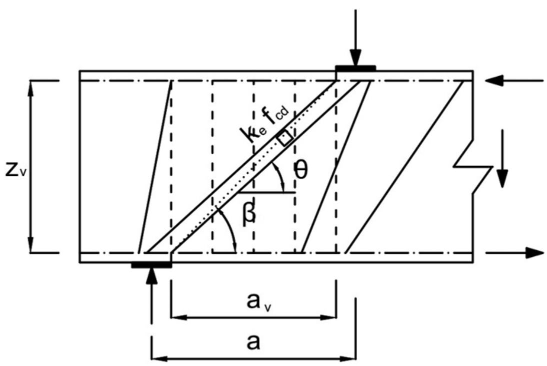

Fig. 2. Load transfer to the support

2.2. Shear resistance without shear reinforcement

The design shear resistance without shear reinforcement is given by:

$$V_{Rd,c} = k_\upsilon \frac{\sqrt{f_{ck}}}{\gamma_C} b_w z_v \quad (f_{ck} \text{ in MPa}) \tag{2.6}$$

where: k_v – a multiplication factor, f_{ck} – characteristic strength of concrete with $\sqrt{f_{ck}}$ is not greater than 8 MPa for $z_v \geq 800$ mm, γ_C – partial factor for concrete, b_w – the effective web width, z_υ – effective shear depth.

For LoA I and members with no significant load, a multiplication factor is defined as:

$$k_v = \frac{0.4}{1 + 750 f_{yd}/E_s} \frac{1300}{1000 + 1.25 z_v} \quad (z_v \text{ in mm}) \tag{2.7}$$

Moreover, the longitudinal reinforcement in the tensile chord of the cross- section in flexure should be capable of transferring the additional force component resulting from shear ($\Delta F_{td} = V_{Ed}$). However, the total area of longitudinal reinforcement should not exceed the area required for the maximum moment.

For LoA II:

$$k_v = \frac{0.4}{1 + 1500\varepsilon_x} \frac{1300}{1000 + k_{dg} z_v} \quad (z_v \text{ in mm}) \tag{2.8}$$

where: f_{yd} – design yield strength of steel, E_s – modulus of elasticity of steel, z_υ – effective shear depth, ε_x – longitudinal strain, k_{dg} – accounts for the roughness of the critical shear crack.

For LoA III, a more detailed cross-sectional analysis is used to determine strain. ε_x.

2.3. Shear resistance with shear reinforcement

2.3.1. General

The design shear resistance should not exceed maximum shear resistance guaranteed by concrete compressive struts, Eq. (2.9). The resistance is a sum the design shear resistance without shear reinforcement Eq. (2.5) and the design resistance provided by shear reinforcement defined by Eq. (2.10) for LoA IIb, or it is equal to the resistance provided by transverse reinforcement only for LoA I and LoA II.

$$V_{Rd} = V_{Rd,c} + V_{Rd,s} \leq V_{Rd,\max} = k_\varepsilon f_{cd} b_w z_v \frac{\cot\theta + \cot\alpha}{1 + \cot^2\theta} \tag{2.9}$$

$$V_{Rd,s} = \frac{A_{sw}}{s_w} z_v f_{ywd} (\cot\theta + \cot\alpha) \sin\alpha \tag{2.10}$$

where: k_ε – the strength reduction factor of concrete carrying the compression field, f_{cd} – design concrete compressive strength, z_υ – effective shear depth, θ – inclination of concrete struts, α – inclination of stirrups, A_{sw} – area of shear reinforcement, s_w – spacing of shear reinforcement, f_{ywd} – the design yield strength of the shear reinforcement.

2.3.2. Level of approximation I

In LoA I, the shear resistance should not be less than the resistance of the same member without shear reinforcement, and the formula gives it:

$$V_{Rd} = V_{Rd,c} \leq V_{Rd,\max} \tag{2.11}$$

The varying $\cot\theta$ for maximum shear resistance can be optimized by:

$$\cot\theta = \cot\beta + \sqrt{1+\cot^2\beta} \leq \cot\theta_{\min} \tag{2.12}$$

where: β – the angle of the failure mechanism (yield line – Fig. 2, dashed line).

The minimum inclination of the compressive stress field is:

$$\cot\theta_{\min} = \begin{cases} 2.2 \text{ for members with significant compression} \\ 1.7 \text{ for reinforced concrete members} \\ 1.2 \text{ for members with significant axial tension} \end{cases} \tag{2.13}$$

The strength reduction factor of concrete carrying the compression field is:

$$k_\varepsilon = 0.55 \tag{2.14}$$

2.3.3. Level of approximation II

Level of approximation II derived using the stress field with concentrated struts method (CSSF) considers the efficiency factor (υ) calculated based on the chord forces in the middle of the shear span. It consists of two approaches, LoA IIa and LoA IIb.

In LoA IIa, the shear resistance should not be less than the resistance of the same member without shear reinforcement, and it is given by the formula:

$$V_{Rd} = V_{Rd,c} \leq V_{Rd,\max} \tag{2.15}$$

The varying $\cot\theta$ for maximum shear resistance can be optimized by:

$$\cot\theta = 1.3\frac{a}{z_v} \leq \cot\theta_{yc} \tag{2.16}$$

The minimum inclination of the compressive stress field Eq. (2.2) is related to the longitudinal strain at the mid-depth of the effective shear depth. ε_x:

$$\cot\theta_{\min} = \begin{cases} \cot(20^\circ + 4000\varepsilon_x) \text{ for ductility class A} \\ \cot(15^\circ + 3000\varepsilon_x) \text{ for ductility class B} \\ \cot(13^\circ + 2500\varepsilon_x) \text{ for ductility class C and D} \end{cases} \tag{2.17}$$

The strength reduction factor of concrete carrying the compression field is:

$$k_\varepsilon = \frac{1}{1.2 + 60\varepsilon_1} \tag{2.18}$$

$$\varepsilon_1 = \varepsilon_x + (\varepsilon_x + 0.001)\cot^2\theta \tag{2.19}$$

In LoA IIb, the shear resistance is defined by Eq. (2.20) $\cot\theta$ according to Eq. (2.21).

$$V_{Rd} = V_{Rd,s} + V_{Rd,c} \leq V_{Rd,\max} \tag{2.20}$$

$$\cot\theta = \cot\left(29^\circ + 7000\varepsilon_x\right) \tag{2.21}$$

2.3.4. Level of approximation III

Level of approximation III, derived using the Stress Field with the Spread Strut method (SSSF), considers full or partial nodal equilibrium. The shear resistance is determined by the applicable conditions of equilibrium and strain compatibility and using appropriate stress-strain models for steel and cracked concrete.

3. Analysis of shear resistance

3.1. Selected design case

The prediction of shear resistance according to Model Code 2020 [3] and Eurocode 2 [18] was studied on a selected design example. A rectangular cross-section $b_w = 250$ mm, $h = 550$ mm was selected, assuming $d = 500$ mm and lever arm $z = 0.9d = 450$ mm. Analyses were performed for two concrete classes, $f_{ck} = 30$ MPa and $f_{ck} = 50$ MPa, with a maximum aggregate size of $d_g = 16$ mm. For both reinforcements, longitudinal and transverse, steel class A with characteristic yield strength $f_{yk} = 500$ MPa was assumed. Following reinforcement was considered: longitudinal bars 2⌀20 mm ($A_s = 6.28$ cm^2) and two types of vertical stirrups ($\alpha = 90^\circ$) 2⌀6 mm ($A_{sw} = 0.56$ cm^2) and 4⌀6 mm ($A_{sw} = 1.12$ cm^2). Spacing of stirrups s_w varies from 50 to 330 mm. The maximum spacing was determined using the condition $s_w = \min\{0.75d; 500\text{ mm}\}$, while the minimum spacing was determined taking into consideration reinforcement assembly. Minimum reinforcement was calculated as $\rho_{w,\min} = (0.08(f_{ck})^{1/2})/f_{yk}$, the same formula recommended by Model Code 2020 and Eurocode 2.

The shear resistance was analysed for three levels of approximation, I, Ia, and IIb, according to Model Code 2020, provided that $\varepsilon_x = 0.0005$ for LoA IIb. The formulas defined in Chapter 2 of this paper were used. Subsequently, the calculations were performed in accordance with Eurocode 2. The design shear resistance was calculated using Eq. (3.1), and the design resistance was limited by the crushing of concrete compression struts, as per Eq. (3.2).

$$V_{Rd} = V_{Rd,s} = \frac{A_{sw}}{s} z\, f_{ywd} \cot\theta \tag{3.1}$$

$$V_{Rd,\max} = \frac{\alpha_{cw} b_w z f_{cd}}{\cot\theta + \tan\theta} \tag{3.2}$$

where: A_{sw} – the cross-sectional area of the shear reinforcement, s – the spacing of the stirrups, z – the inner lever arm ($z = 0.9d$), f_{ywd} – the design yield strength of the shear reinforcement, θ – the angle between the concrete compression strut and the beam axis perpendicular to the shear force ($1.0 \leq \cot\theta \leq 2.5$), α_{cw} – a coefficient taking account of the state of the stress in the compression chord, $\alpha_{cw} = 1.0$ for reinforced concrete structures, b_w – the width between tension and compression chords, f_{cd} – the design concrete compressive strength.

3.2. Analysis of shear resistance

The shear resistance in the support zone, according to Model Code 2020, was analysed for different types of stirrups, their spacing, and concrete classes. Condition for minimum percentage of reinforcement ($\rho_w \geq \rho_{w,\min}$) and resistance ($V_{Rd,s} + V_{Rd,c} \leq V_{Rd,\max}$) was fulfilled. The calculations were performed for recommended levels of approximation, which differ in their approaches to predicting resistance and coefficients, as well as in the methods used to calculate the inclination angle of the concrete strut. For LoA I and LoA IIa, the resistance is based exclusively on transverse reinforcement, whereas for LoA IIb, it considers transverse reinforcement as well as concrete. The obtained results were summarized in Table 1. Values of the shear resistance $V_{Rd,\max}$ according to Eurocode 2 were calculated using Eq. (3.2), assuming $\cot\theta$ to be the same as in the calculation according to Model Code 2020, and the results were presented in Table 2.

Table 1. Resistance $V_{Rd,\max}$ and $\cot\theta$ according to Model Code 2020

f_{ck} = 30 MPa, f_{yk} = 500 MPa, $\rho_{w,\min}$ = 0.0009, ε_x = 0.0005					
Level I		Level IIa		Level IIb	
$\cot\theta$ Eq. (2.13)	$V_{Rd,\max}$ Eq. (2.9)	$\cot\theta$ Eq. (2.17)	$V_{Rd,\max}$ Eq. (2.9)	$\cot\theta$ Eq. (2.21)	$V_{Rd,\max}$ Eq. (2.9) for $\cot\theta$ from Eq. (2.21)
1.7	0.54081 MN	2.4751	0.43871 MN	1.5697	0.43871 MN
f_{ck} = 50 MPa, f_{yk} = 500 MPa, $\rho_{w,\min}$ = 0.0011, ε_x = 0.0005					
1.7	0.90135 MN	2.4751	0.73118 MN	1.5697	0.73118 MN

Table 2. Resistance $V_{Rd,\max}$, and $\cot\theta$ according to EN 1992-1-1:2004 (EC2)

f_{ck} = 30 MPa, f_{yk} = 500 MPa, $\rho_{w,\min}$ = 0.0009		f_{ck} = 50 MPa, f_{yk} = 500 MPa, $\rho_{w,\min}$ = 0.0011	
$\cot\theta$	$V_{Rd,\max}$	$\cot\theta$	$V_{Rd,\max}$
1.7	0.5118 MN	1.7	0.78663 MN
2.4751	0.41263 MN	2.4751	0.65190 MN

Comparing the results of maximum shear resistance limited by concrete compression struts, higher values are obtained for Model Code 2020 than for Eurocode 2. One reason is the detailed analysis of deformation in zones where bending moment and shear force act simultaneously.

The calculations were performed in Microsoft Excel and plotted as diagrams (Fig. 3 to Fig. 6). To facilitate comparison, the results were scaled using the coefficients f_{yk}/f_{ck}, for the reinforcement ratio, and $K = b_w z f_{ck}/\gamma_c$ for resistance. Designations MCI, MCIIa, and MCIIb are related to the Model Code 2020, where the Roman numeral indicates the level of approximation. Designations EC(I), EC(IIa), and EC(IIb) are related to Eurocode 2, and the Roman numbers indicate that the value of $\cot\theta$ was assumed to be the same as for Model Code 2020.

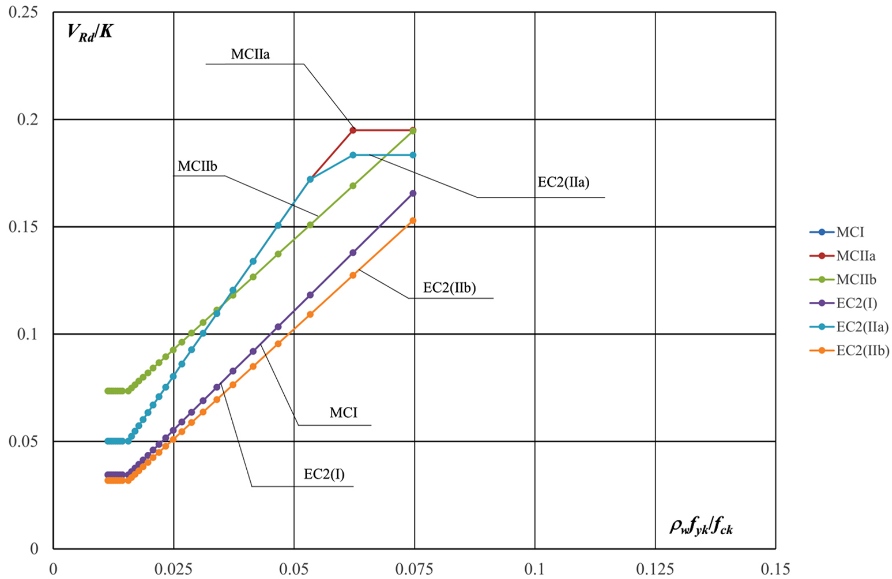

Fig. 3. Shear resistance according to MC2020 (Level I, IIa, IIb) and EN 1992-1-1:2004 (EC2): concrete f_{ck} = 30 MPa, stirrups 2⌀6 mm

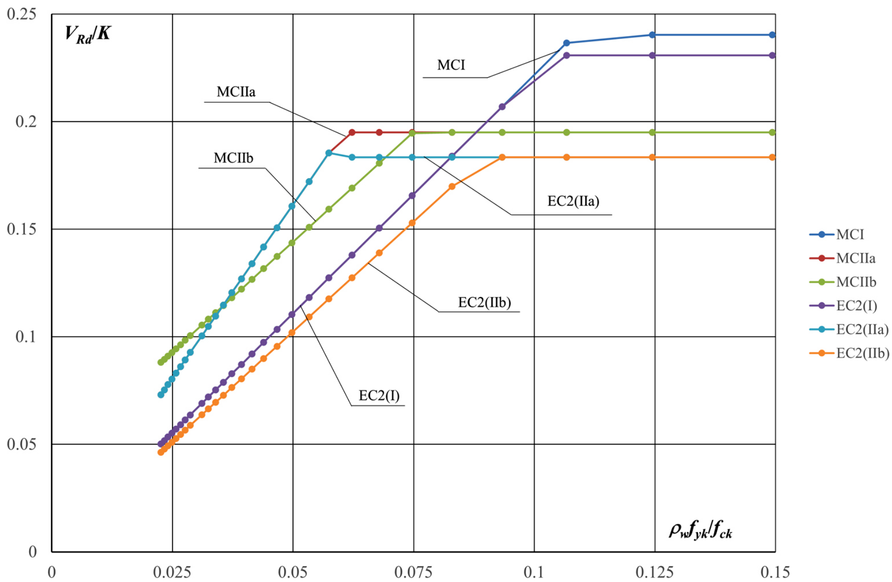

Fig. 4. Shear resistance according to MC2020 (Level I, IIa, IIb) and EN 1992-1-1:2004 (EC2): concrete f_{ck} = 30 MPa, stirrups 4⌀6 mm

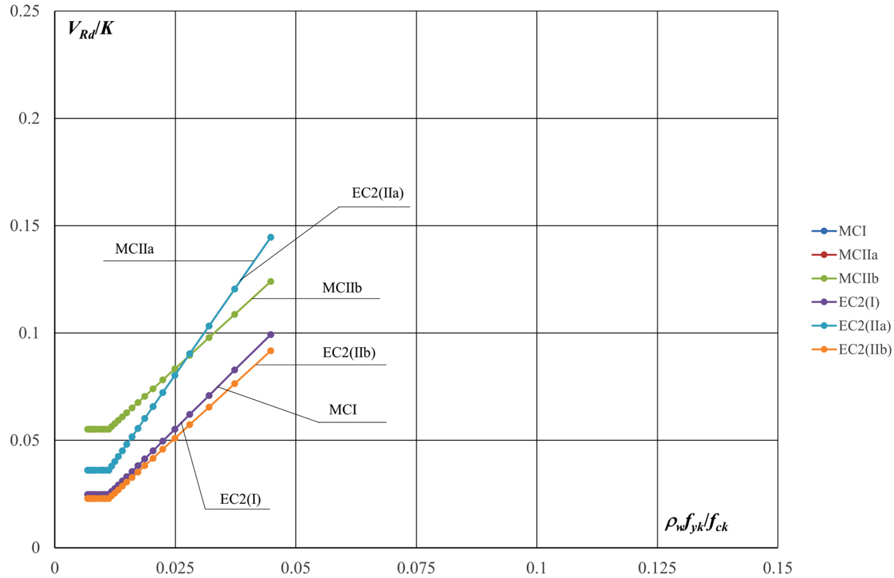

Fig. 5. Shear resistance according to MC2020 (Level I, IIa, IIb) and EN 1992-1-1:2004 (EC2): concrete f_{ck} = 50 MPa, stirrups 2⌀6 mm

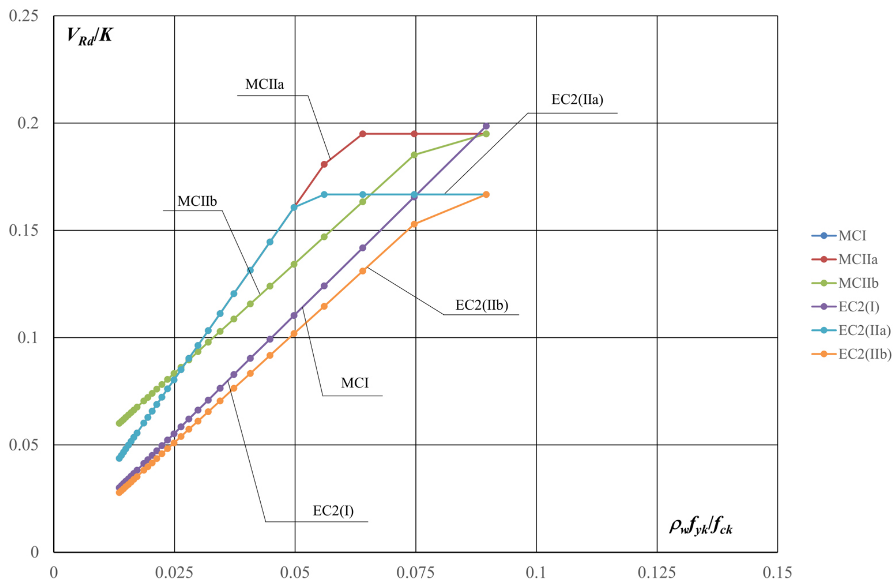

Fig. 6. Shear resistance according to MC2020 (Level I, IIa, IIb) and EN 1992-1-1:2004 (EC2): concrete f_{ck} = 50 MPa, stirrups 4⌀6 mm

Analysing the results presented in Fig. 3 to Fig. 6, it can be noticed that the shear resistance calculated for Model Code 2020 LoA I coincides with results for EC2 for assumed $\cot\theta = 1.7$, except for the case of $f_{ck} = 30$ MPa and a high amount of shear reinforcement ($A_{sw} = 1.12$ cm^2), as shown in Fig. 4. A difference is noticed for $\rho_w \geq 0.64\%$, when the maximum force $V_{Rd,\max}$ governs. It is higher for MC2020 LoA I, Table 1 and Table 2. Comparing resistance for MC2020 LoA IIa and EC2 for $\cot\theta = 2.4751$ (Fig. 3, Fig. 4) and $f_{ck} = 30$ MPa, it can be noticed that the results for MC 2020 are higher for smaller as well as high amounts of transverse reinforcement, $\rho_w \geq 0.37\%$, which is conditioned by concrete. A similar situation occurs for $f_{ck} = 50$ MPa with a higher amount of shear reinforcement ($A_{sw} = 1.12$ cm^2), Fig. 6. This tendency can be seen for $\rho_w \geq 0.64\%$. Below that shear reinforcement value, the shear resistance according to MC2020 and EC2 is the same. This limitation helps decrease the probability of over-reinforcement in the support zone. Another observation can be done for $f_{ck} = 50$ MPa and transverse reinforcement $A_{sw} = 0.56$ cm^2 (Fig. 5). In this case, the shear reinforcement governs, and the resistance of concrete in compression is not fully utilized. It can be stated that using too small an amount of shear reinforcement, despite providing adequate resistance, is not economical and is not recommended. On the other hand, comparing the resistance given in MC 2020 LoA IIb for all designed cases (Fig. 3 to Fig. 6), it is higher than that of EC 2. In both cases, the shear resistance provided by shear reinforcement was calculated for the same $\cot\theta = 1.5697$, while the maximum shear force $V_{Rd,\max}$ for $\cot\theta$ as for LoA IIa. The reasoning behind that observation is that for MC2020 LoA IIb, the design shear resistance is a sum of resistance guaranteed by shear reinforcement and concrete. Similarly, as discussed above, after reaching the value of $V_{Rd,\max}$ (for $f_{ck} = 30$ MPa, $\rho_w \geq 0.50\%$ and for $f_{ck} = 50$ MPa $\rho_w \geq 0.75\%$, both cases $A_{sw} = 1.12$ cm^2), the resistance of the concrete compression strut governs, Fig. 4 and Fig. 6.

Comparing the results for LoA IIa and LoA IIb, it can be noticed that for $\rho_w < 0.20\%$ the shear resistance is higher for LoA IIb, then it changes (Fig. 4 and Fig. 6). Furthermore, analysing the results for shear reinforcement $A_{sw} = 0,56$ cm^2 and $\rho_w < \rho_{w,\min}$, both for concrete $f_{ck} = 30$ MPa as well as $f_{ck} = 50$ MPa, the design resistance given by MC2020 and EC2 is smaller than the design resistance of the cross-section without shear reinforcement (Fig. 3 and Fig. 5). The failure may occur due to exceeding tensile strength of concrete. In this zone, diagonal cracks are caused by principal tensile stresses coming from the combined action of the bending moment and the shear force. Such a situation will not have a place if $\rho_w \geq \rho_{w,\min}$. For $A_{sw} = 1,12$ cm^2, all analysed cases fulfil the condition of $\rho_w \geq \rho_{w,\min}$ (Fig. 4 and Fig. 6).

4. Summary and conclusions

In this paper, the shear resistance according to EN 1992-1-1:2004 (EC2) and the new Model Code 2020 was analysed. It was observed that the detailed analysis of the support zone proposed in MC 2020, level of approximation II b, leads to the use of a smaller amount of shear reinforcement. It results from the participation of concrete in the shear resistance. In the case of MC 2020 levels of approximation, I and IIa, and EC2, the results coincide because the contribution of concrete to shear resistance was neglected. MC 2020 and EC2 give the most severe criteria for the design shear resistance of the support zone. Model Code 2020 offers more possibilities for the designer, but it requires an individual approach and greater design experience, especially at level III approximation.

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Nośność na ścinanie elementów żelbetowych według Model Code 2020

Słowa kluczowe: nośność na ścinanie, żelbet, Model Code 2020, Eurokod 2, strefa przypodporowa

Streszczenie:

Zniszczenie elementów konstrukcji żelbetowej na skutek oddziaływania sił poprzecznych jest problemem złożonym, na który między innymi ma wpływ wielkość i rodzaj przyłożonego obciążenia oraz wymiary i kształt przekroju poprzecznego elementu oraz właściwości materiałów konstrukcyjnych. Ponadto ścinanie jest ściśle powiązane z głównymi naprężeniami rozciągającymi. Przekroczenie przez główne naprężenia rozciągające wytrzymałości betonu na rozciąganie powoduje powstanie rys ukośnych, które w betonie wyodrębniają ściskane krzyżulce betonowe nachylone pod katem θ do osi elementu. Mechanizm zniszczenia na skutek ścinania jest zjawiskiem skomplikowanym wynikającym z ukośnych pęknięć, częściowego obrotu elementu, zazębienia się ziaren kruszywa i odspojenia podłużnego zbrojenia rozciąganego od betonu. Jako pierwszy ten mechanizm został opisany przez Mörsha za pomocą modelu kratownicowego. Model ten składał się z pasów górnych i dolnych utworzonych odpowiednio z betonu ściskanego i podłużnego zbrojenia rozciąganego, ściskanych krzyżulców betonowych powstałych pomiędzy rysami ukośnymi i nachylonych do osi elementu pod kątem 45° oraz zbrojenia poprzecznego. Model ten stanowił podstawę do dalszych badań. Rozwój modeli idealizacji zjawisk obserwowanych w badaniach głównie stref przypodporowych belek, a także metod określania nośności elementów żelbetowych na ścinanie, doprowadził do opracowania podejścia zaproponowanego w Model Code 2020. Jest ono oparte na modelu strut-and-tie i pozwala na weryfikację nośności na ścinanie na trzech poziomach przybliżenia. W tym artykule przedstawiono i zobrazowano to nowe podejście dla poziomów przybliżenia I, IIa i IIb, a następnie porównano z Eurokodem 2. W przypadku nośności na ścinanie zgodnie z Eurokodem 2 przyjęto takie samo nachylenie betonowego pręta ściskanego $\cot\theta$ jak w Model Code 2020. Prognozowanie nośności na ścinanie badano na prostokątnym przekroju poprzecznym, przyjmując dwie klasy betonu C30/37 i C50/60 i dwa typy strzemion pionowych (strzemiona $\varnothing 6$ dwuramienne i $\varnothing 6$ czteroramienne) o różnym rozstawie. Aby ułatwić interpretację wyników, zostały one przeskalowane za pomocą współczynników i przedstawione w formie graficznej. Podczas analizy pracy strefy przypodporowej zaobserwowano, że określenie nośności według Model Code 2020 (poziom IIb) prowadzi do zastosowania mniejszej ilości zbrojenia na ścinanie. Związane jest to z uwzględnieniem w tym przypadku nośności betonu na ścinanie. W przypadku I i IIa poziomu dokładności analizy według MC2020 i normy EN 1992-1-1:2004 uzyskane wyniki są zbieżne, ponieważ w obu normach została pominięta praca betonu w strefie ścinania. MC2020 (poziom I) i EN 1992-1-1:2004 (EC2) dają najostrzejsze kryteria zapewnienia nośności strefy przypodporowej ze względu na ścinanie. Bardziej zaawansowane metody projektowania są ekonomiczne, ale wymagają większego doświadczenia projektanta.

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