Pavlo Vegera, Roman Khmil, Zinoviy Blikharskyy

THE SHEAR CAPACITY OF REINFORCED CONCRETE BEAMS WITH DIFFERENT SHEAR SPAN TO EFFECTIVE DEPTH RATIO

Statement of problem

Reinforced concrete constructions are widespread buildings elements in the world, then it is necessary to know main principles of their stress strain state and perform reliable design of them. Special attention should be paid to the design of the RC beams on the shear strength. Many researches investigate this direction with the aim to develop and improve the basic provisions of shear strength calculation [1-5]. Most of these researches develop shear failure of beams from moment influence. This type of failure will occur when working reinforcements lose restrains in a supporting area. But when this type has occurred, it indicates a design flaw. The main type of fracture should be destruction from influence of shear efforts. Destruction of RC beam by this type is sudden, unpredictable and it occurs with more effort than the first type at the same reinforcement. Researching this type of failure allows better design and more effective use reinforcement. Exploring stress strain state is a necessary task placed before researchers.

Important task is development and researching existing [6] and new methods of calculation [7]. Such investigation allows better understanding stress-strain state of RC beam on the shear capacity. In European [8] and Ukrainian norms [9] remain many factors and variables which don't have recommendation or do not succeed in determining shear capacity of RC beam. These are such factors as: shear span to effective depth ratio, the angle between the compressed concrete elements and conventional beam axis which is perpendicular to the transverse force, collaboration between concrete and reinforcement in inclined cross-section. Determined factors, given above and improving methods of calculation, allow to perform design more economically.

1. The aim and the objective of research

In this article the authors explain the following:
- determine the influence of load location on the shear strength of reinforced concrete beams;

– compare stress strain state for RC beams with different shear span to effective depth;
– review current and determine optimum relationship for RC beams shear capacity calculation;
– compare the theoretical values with the experimental ones.

2. Experimental data

2.1. Materials and construction of the samples

To achieve the aim of research a sample of concrete beam with 2100 mm length, 100 mm width, and 200 mm height was selected. As the beam's tension reinforcement a A400C ϕ22 mm rebar was chosen (according to DSTU 3760:2006). The A400C ϕ12 mm rebar (according to DSTU 3760:2006) was chosen as compressed reinforcement. Transverse reinforcement - A240C ϕ8 mm rebar (DSTU 3760:2006) located in the supporting area with step 100 mm (Figs. 1, 2).

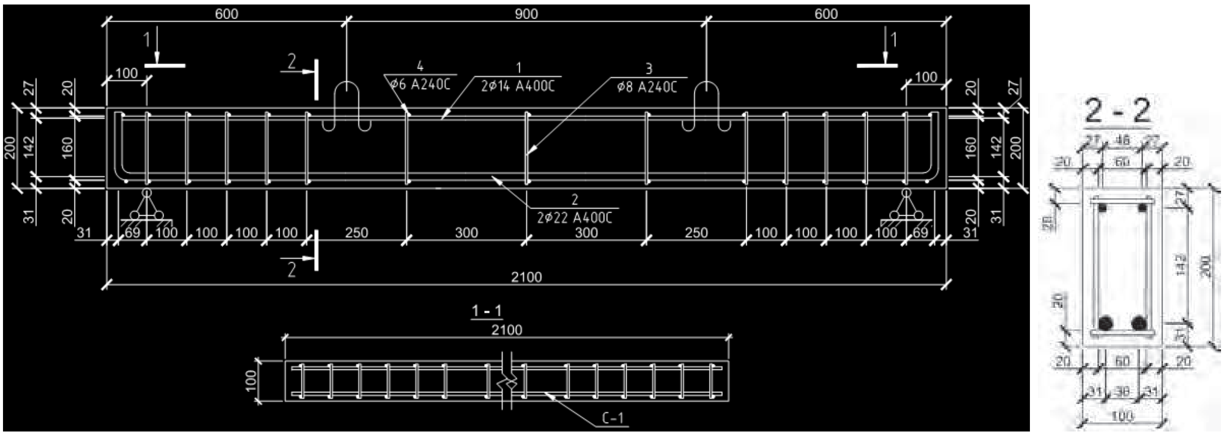

Fig. 1. Reinforcement and dimensions of the designed beam

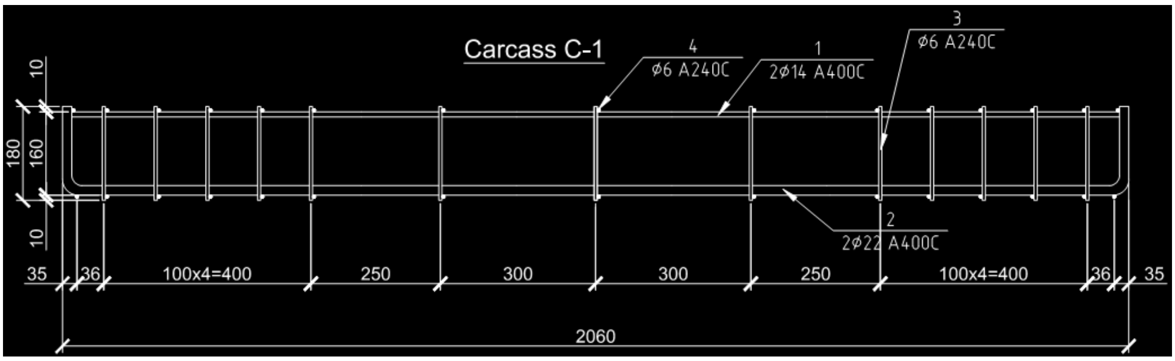

Fig. 2. Carcass from rebar

The reinforced concrete beam was designed to provide flexural bearing capacity according to recommendations [9].

2.2. Placement of the main measuring devices

For measuring deformation we used dial indicators, deflection and strain gauges. Dial indicators I-0.01 were used for measuring deformation of working reinforcement and concrete (Fig. 3).

a)

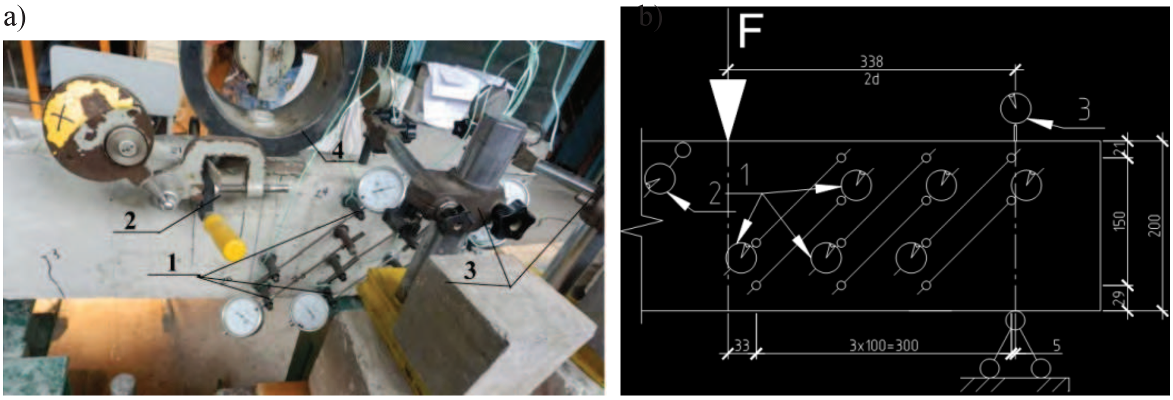

Fig. 3. The placement of measuring devices on the supporting area: a) placement of devices on experimental sample: b) the layout of dial indicators; 1 - dial indicators for deformations measurement, 2 - deflection gauges, 3 - holders with dial indicators, 4 - ring dynamometer

Strain gauges were pasted with epoxy glues to the transverse rebar. Deflection gauges were used for fixed deflection of the RC beam (Fig. 4).

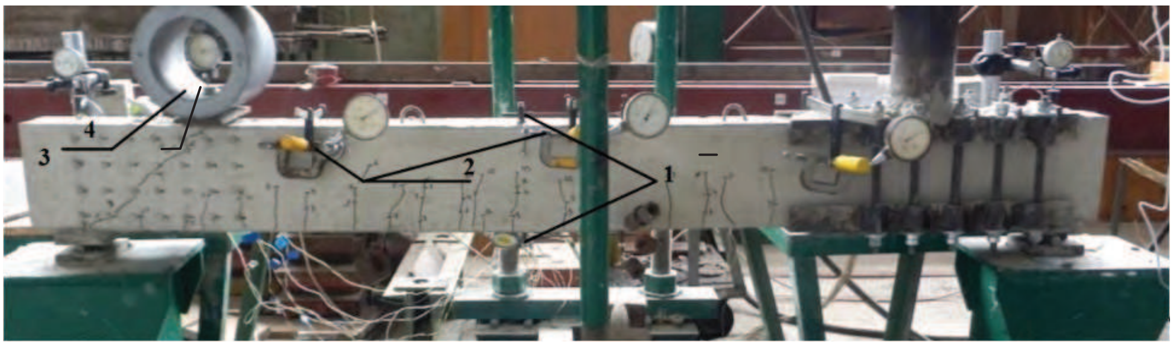

Fig. 4. Placement of devices on experimental sample: 1 - dial indicators for deformations measurement, 2 - deflection gauges, 3 - holders with dial indicators, 4 - ring dynamometer

They are fixed on the beam in the center and 500 mm from center in both sides.

RC beams were projected from concrete class C32/40 with $f_{ck} = 32$ MPa. The concrete class was confirmed by testing concrete cubes and prisms.

The transversal reinforcement of column was taken A240C (smooth surface of rebar) with experimental yield strength 363 MPa and shear design strength to 260 MPa. The longitudinal rebar (compressed and tensile) was taken A500C with yield strength 640 MPa.

2.3. Methodology of experiments

Beams were tested by loading to failure. Feature of the researching was testing every beam twice. As we know beam failure in both inclined cross-section when it was tested on the shear. For the economy material and cost of labor one cross-section was reinforced by metal jacket (Figs. 5, 6).

For preventing deformation in the concrete the metal jacket was mechanically pre-stressed by heating.

This testing methodology shows reliable results for test beam on the shear but there are influence on the beams curvature and deformation of the normal cross-section.

Load applied stages by 1/10 from theoretical failure by shear force. On the every stage we made excerpt 10 min and fixed values of measuring devices. Load controlled by ring dynamometer which was passed load from distributive beam to the testing cross-section.

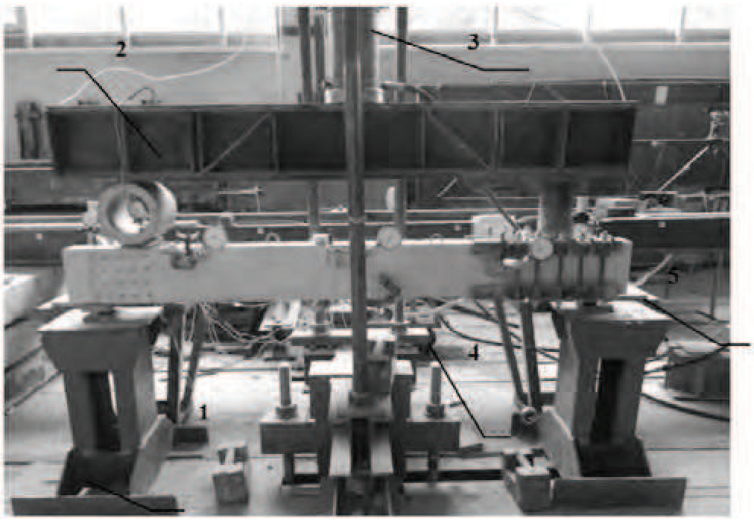

Fig. 5. Testing first inclined cross-section: 1 - support, 2 - distributive metal beam, 3 - hydraulic crank, 4 - testing beam, 5 - metal jacket

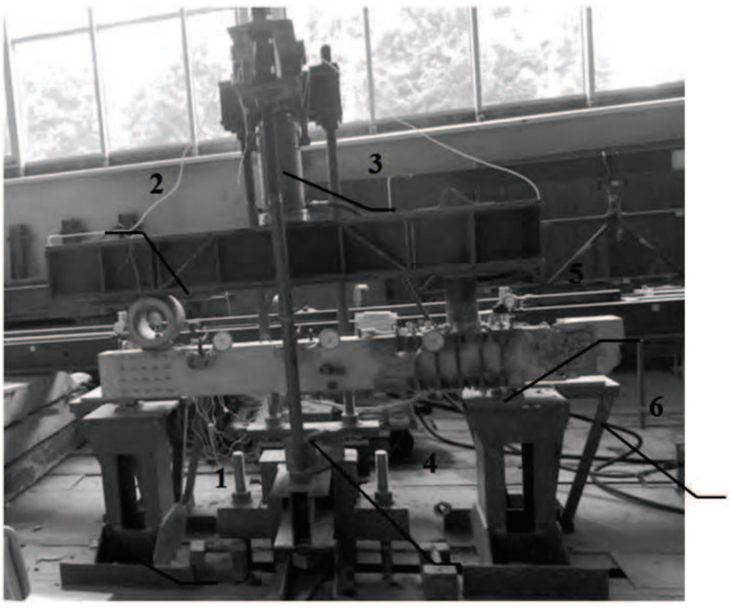

Fig. 6. Testing second inclined cross-section: 1 - support, 2 - distributive metal beam, 3 - hydraulic crank, 4 - testing beam, 5 - metal jacket, 6 - crashed cross-section

Proposed methodology showed good testing's convergence with lower cost of labor and materials than with conventional methodology.

2.4. The shear capacity of RC beams

To achieve the task we tested three samples (six cross-sections). Variable parameter was different shear span to effective depth ratio which equaled 1, 1.5 and 2. Strength of the flexural was designed twice higher than shear strength.

Beams marking were as follows: BO - beam ordinary, the first digit - serial number, the second digit - prototype number, and the third digit - section number. For example BO 2.1-2 means that the tested example comes from second series of the first beam of the second section.

Results of experimental tests and main beams parameters are shown in Table 1.

TABLE 1

Results of experimental testing carrying capacity of the RC beams on shear strength

Types of the beams	Types of the cross-sections	Cross section bxh [mm]	Span of the beam l_0 [mm]	Shear span to depth ratio a/d	Experimental shear load [kN]	The divergence between twins [%]
BO 2.1	BO 2.1-1	201x106	1900	1	250	6.8
	BO 2.1-2		1650	1	267	
BO 2.2	BO 2.2-1	199x98	1900	1.5	186	3.9
	BO 2.2-2		1650	1.5	179	
BO 2.3	BO 2.3-1	202x98	1900	2	150	2.1
	BO 2.3-2		1650	2	147	

As we can see from Table 1, the discrepancy between twins was less than 7%, which shows high convergence for using improved methodology for testing beams on the shear.

Analyzing results of experiments, the following conclusions were made:

– shear strength was higher with lower shear span to effective depth ratio;
– beams collapse was more sudden and brittle when shear span to depth ratio equaled 1 (Figs. 7, 8);
– the transversal reinforcement increases the total carrying capacity by improving the anchoring of the longitudinal reinforcement and perception shear deformation.

a) b) c)

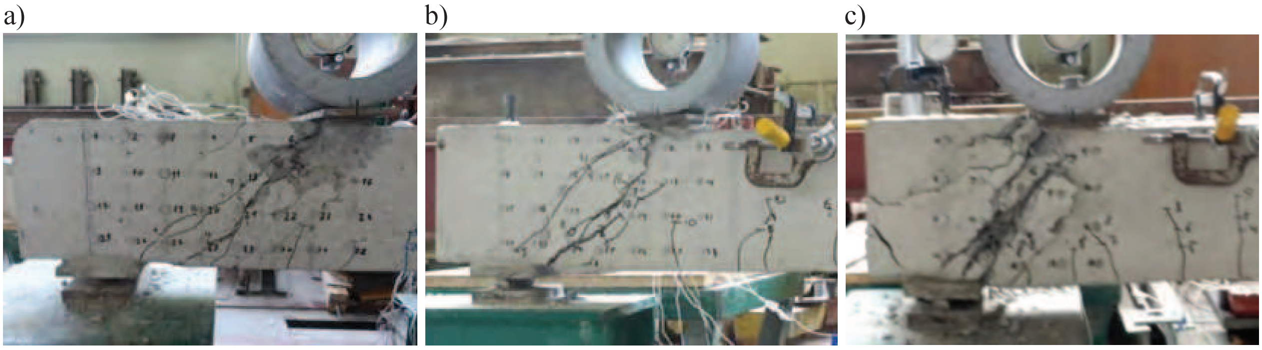

Fig. 7. Experimental samples destroyed: a) BO 2.1-1, b) BO 2.2-2, c) BO 2.3-1

Deformations of the inclined cross-section were shown in Figures 8-10. There are given deformations with value of width of inclined crack. In the next graph average values from all dial indicators, which were fixed on inclined cross-section and measured tension concrete deformations are shown.

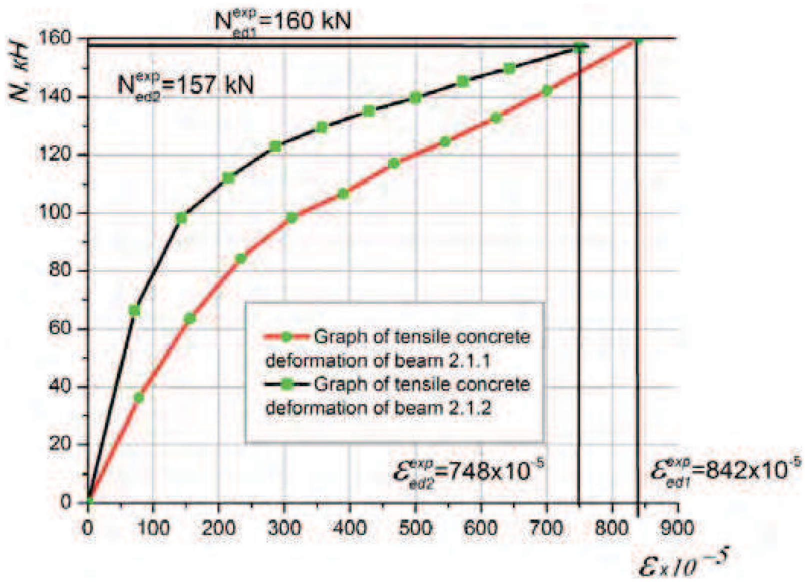

Fig. 8. Graphics of averaged values of deformation for the beam BO 2.1

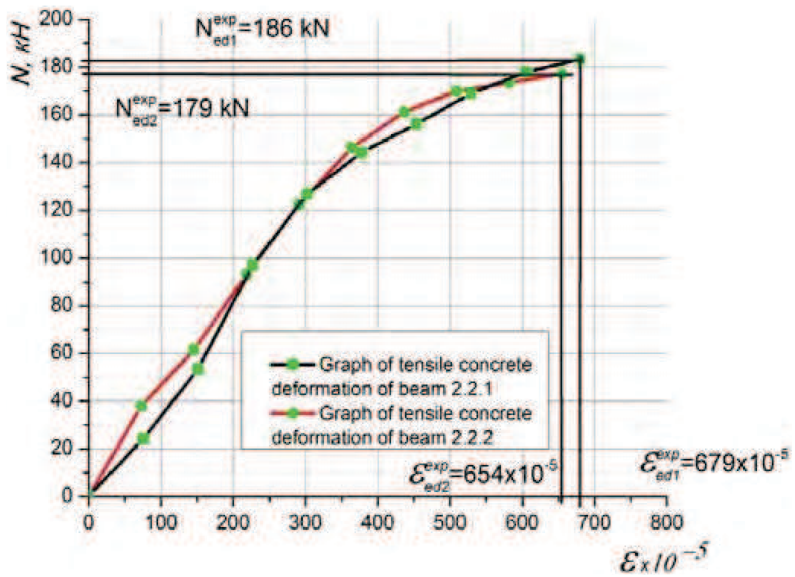

Fig. 9. Graphics of averaged values of deformation for the beam BO 2.2

Comparing deformation of different inclined cross-sections on the same beam we can conclude that values of deformation on the same stage are close in meaning. Analyzing maximum values of deformation we can see when increasing shear span to effective depth ratio maximum deformations are lower. These indexes showed higher tension in inclined cross-section what confirmed more rapidly destroying beams at lower shear span to effective depth ratio.

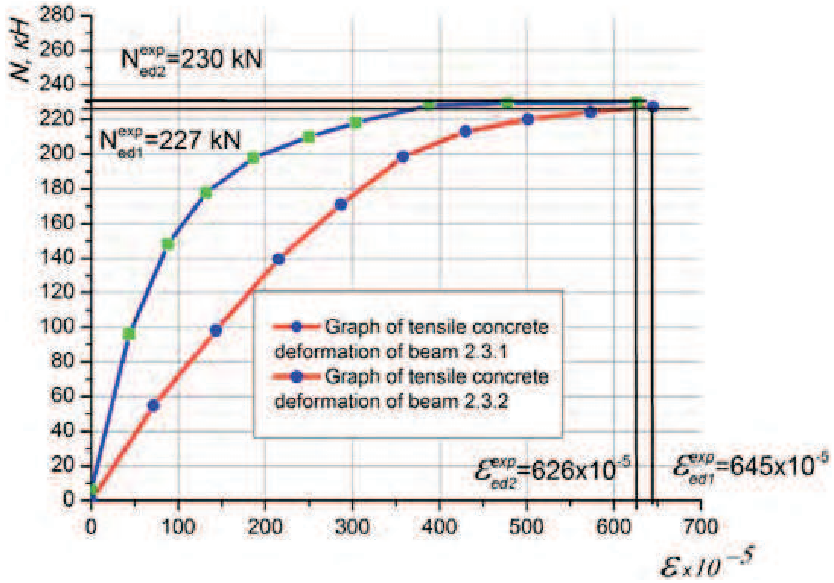

Fig. 10. Graphics of averaged values of deformation for the beam BO 2.3

3. Calculation shear carrying capacity of RC beams

Ukrainian codes [9, 10], which are based on the Eurocode [8], proposed to calculate carrying capacity by equation:

$$V_{Rd,s} = \frac{A_{sw}}{s_w} \cdot z \cdot f_{ywd} \cdot cot\theta \quad (1)$$

where θ - the angle between the compressed concrete elements and conventional beam axis which is perpendicular to the transverse force (the angle θ is limited, the limit values $cot\theta$ are taken within $1 \leq cot\theta \leq 2.5$), z - shoulder of internal pair for the element with constant height of cross-section, which corresponds to the bending moments in the element under consideration (in the calculation of shear of reinforced concrete elements, in the absence of axial forces approximately value can be taken 0.9 d, [mm]); A_{sw} - sectional area of transverse reinforcement [cm^2], s_w - step transverse rods [mm]; f_{ywd} - resistance calculated yield strength of transverse reinforcement [MPa].

For calculation in equation (1) highest values $cot\theta$ were accepted [1]. But shear capacity RC beam is lower than experimental data (Tab. 2).

This relationship determines shear resistance using worst case: beams failure with dominating bending moment. This type of destruction comes when working rebar has lost its anchoring.

For the case when tensile reinforcement fully anchoring, relationship (1) will not take high comparison, then we have overrun of materials. Proposed too calculation shear strength of RC beams taking into account strength of concrete, in forms:

$$V_{Rd} = V_{Rd,s} + V_{Rd,c} \cdot \gamma_M \tag{2}$$

where: $V_{Rd,s}$ - carrying capacity of transverse reinforcement of RC beams on the shear calculated by relationship (2); $V_{Rd,c}$ - carrying capacity of concrete in shear zone; $\gamma_M = 0.8$ - coefficient, which is taking into account surround reduction of the supporting area of concrete by transverse reinforcement.

TABLE 2

Theoretical and experimental shear capacity of RC beams

Types of the beams	Types of the cross-section	Cross-section bxh [mm]	Span of the beam l_0 [mm]	Shear span to depth ratio, a/d	Experimental shear load [kN]	Average values [kN]	Theoretical shear load [kN]	The divergence [%]
BO 2.1	BO 2.1-1	201x106	1900	1	250	258.5	96.34	62
	BO 2.1-2		1550	1	267			
BO 2.2	BO 2.2-1	199x98	1900	1.5	186	182.5	96.34	47
	BO 2.2-2		1750	1.5	179			
BO 2.3	BO 2.3-1	202x98	1900	2	150	148.5	96.34	35
	BO 2.3-2		1650	2	147			

The code [10] doesn't have guidance on the definition *cotθ*. The angle *θ* invited to consider as angle between compressed concrete strut and conventional beam axis. Compressed concrete strut placement from applied power to constrain (Fig. 11) [10].

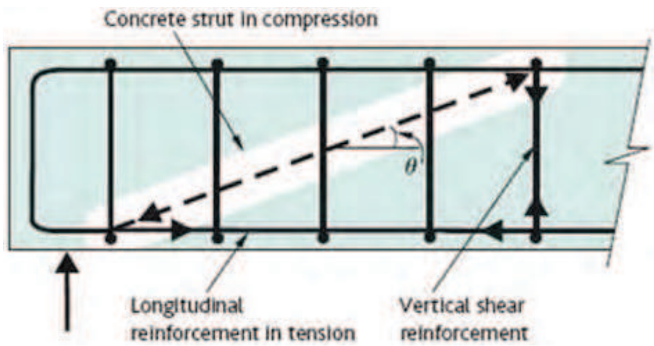

Fig. 11. Strut inclination method

Then values of *cotθ* can be calculated as:

$$cot\theta = \frac{a}{d} \tag{3}$$

where: a - distance from constrain to point of applied force, d - efficiently depth of cross-section. So we are taking into account placement of the load.

Values of $V_{Rd,c}$ proposed to calculation using equation:

$$V_{Rd,c} = \left[\left(\frac{5 \cdot d}{a} \right)^{1/3} \cdot C_{Rd,c} \cdot \left(1 + \sqrt{\frac{200}{d}} \right) \cdot \left(100 \cdot \rho_1 \cdot f_{ck} \right)^{2/3} \right] \cdot b_w \cdot d \tag{4}$$

where: $C_{Rd,c}$ - the minimum value (normalized) of shear strength for concrete [MPa], ρ_1 - coefficient of reinforcing cross-section by the longitudinal tensile reinforcement, f_{ck} - characteristic value of concrete compressive strength at 28 days [MPa], b_w - smallest cross-section width in the tensile zone [mm].

Results of calculation carrying capacity of RC beams on the shear are shown in Table 3.

TABLE 3

Theoretical and experimental carrying capacity of RC beams on the shear

Types of the beams	Types of the cross-section	Shear span to depth ratio, a/d	Experimental shear load [kN]	Average values [kN]	Theoretical shear strength by DSTU		Theoretical shear strength by improved method	
					value [kN]	divergence [%]	value [kN]	divergence [%]
BO 2.1	BO 2.1-1	1	227	228.5	96.34	62	193.6	18.1
	BO 2.1-2	1	230					
BO 2.2	BO 2.2-1	1.5	186	182.5	96.34	47	161.14	13.3
	BO 2.2-2	1.5	179					
BO 2.3	BO 2.3-1	2	160	158.5	96.34	35	154.57	2.5
	BO 2.3-2	2	157					

Shear strength calculation of RC beam using equation (2) shows high convergence for different shear span to effective depth ratio. Also this equation permits to estimate stress strain state in inclined cross-section.

Conclusions

After conducted researches we can make next conclusions:

- the researching of RC beams on the shear using improved methodology with testing one beam twice shows good convergence - less than 7%;
- with increasing shear span to effective depth ratio maximum deformations are lower;
- the destroying of RC beams with lower shear span to effective depth ratio passes rapidly with crushing of concrete;
- the empirical relationship for calculating shear capacity of RC beams was proposed. It includes the strength of transverse reinforcement and compressed concrete in inclined cross-section. This shows good convergence (up to 18%) unlike the method from code [10] (up to 62%).

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Nośność na ścinanie belek żelbetowych z różnymi proporcjami długości odcinka ścinania do wysokości użytecznej przekroju

Streszczenie

W artykule przedstawiono wyniki badań eksperymentalnych belek żelbetowych z różnymi proporcjami długości odcinka ścinania do wysokości użytecznej przekroju. Zaproponowano i wykonano obliczenia, w których uwzględniono współpracę betonu i stali.

Słowa kluczowe: belki żelbetowe, nośność na ścinanie

Shear capacity of reinforced concrete beams with different shear span to effective depth ratio

Abstract

In the article the results of experimental research of reinforced concrete beams with different shear span to effective depth ratio are described. It was proposed and tested calculation which includes the joint operation of concrete and reinforcement in the old section.

Keywords: reinforced concrete beams, shear capacity