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Local action of loading on concrete cubes

Miejscowe działanie obciążenia na kostki betonowe

Abstract

In the work, different approaches to projecting concrete elements have been considered, taking into account concrete deformation under tension in a casing around the crushing area at different levels of loading. The purpose of the investigations was the detection of the principal factors, which discern the taken empirical approaches to the computing models from the experimental character of tension strain distribution and concrete deterioration around the loading area. There have been determined, through an experiment, the lateral strains of the concrete tension along the perimeter of the side cube faces with the size of cube edges that equal to 300 mm with the formation of the cracks and up to the deterioration. The approach to calculations of the effect made by the samples of the above-mentioned type on local vertical loading with the reducing coefficient of their working conditions should be considered in the regulatory documents.

Keywords: local loading, stress, strain, deformation

Streszczenie

W artykule przedstawiono i porównano różne podejścia do projektowania elementów betonowych z uwzględnieniem odkształcenia betonu na rozciąganie w obejmie wokół pola zgniecenia przy różnych poziomach obciążenia. Celem badań było określenie głównych czynników, które odróżniają podejścia empiryczne do schematów obliczeniowych dla częściowo obciążonych obszarów od eksperymentalnego charakteru rozkładu deformacji rozciągania oraz zniszczenia betonu obejmy wokół powierzchni obciążenia. Doświadczalnie określono poprzeczne naprężenia rozciągające betonu na obwodzie bocznych powierzchni kostki o wymiarach żeber 300 mm przy powstawaniu pęknięć i do zniszczenia.

Słowa kluczowe: obciążenie miejscowe, naprężenie, odkształcenie, deformacja

1. Introduction

The local surface compression of concrete in structural elements of a square section is quite common in cases of the transmission of loading through metal centring spacers of different cross-sections from the above-placed elements onto the ones that are placed lower.

The probability of bearing failure under local loading of concrete elements has been practically proven, but in different normative documents, this nature of destruction is described by way of using various calculation designs. When calculating local loading on purely concrete elements according to the old Construction Norms and Regulations, SNIP 3], the following condition should be met:

$$F_{loc} \leq \psi R_{b,loc} A_{loc,1} \tag{1}$$

Norms [2–4, 10] use the same approach to the calculation, but they do not allow to assess the level of loading during the initiation and formation of vertical micro-cracks and macro-cracks.

The formation of vertical cracks in concrete should be considered as its transition typical condition, for practically this loading is the onset of the process of destruction of concrete in time and, in addition, subject to the conditions of its use. Therefore, the assessment of deformation characteristics of the early stage micro-crack formation in concrete and its boundary deformation during concrete macro-crack formation, with its transverse tension through compression by longitudinal forces, is a very topical task.

Of course, one should also pay attention to the nature of the kinematics of the crack formation and destruction of concrete structures during compression by longitudinal forces in the event of the transfer of loading onto them through the metal centred spacers of different sections.

2. Analysis of regulatory approaches and studies

The calculation of concrete elements for local bearing according to the normative literature is performed under the effect of compression force on the limited area taking account of the increased resistance of concrete to the compression within the area of bearing due to the formation of the volumetric stress state of the concrete that is under it. The issue of actual concrete tension deformation in a holder around the area of bearing at different levels of loading has not been sufficiently dealt with.

In the old norms [3], the calculation of the elements for bearing was performed using dependence (1). According to it, the main factor of influence adopted for heavy concrete of grade above B7,5 is the formula

$$\phi_b = \sqrt[3]{A_{loc2} / A_{loc1}} \leq 2,5 \tag{2}$$

which deals with the limited value of the root of the cubic relationship of the calculated reference area of bearing A_{loc2} to the area of direct bearing A_{loc1}. The same approach is offered by the valid norms [2, 4].

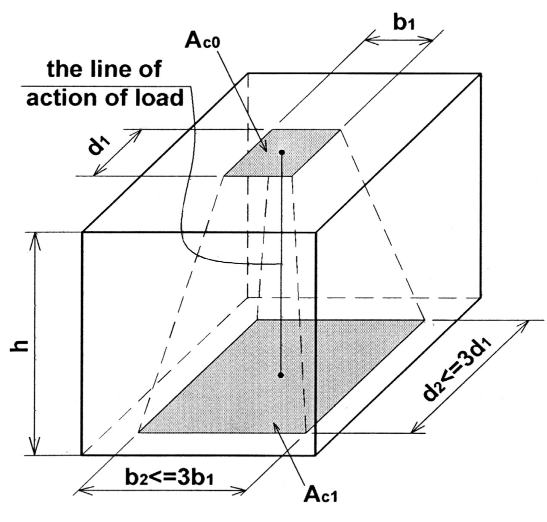
The height of concrete elements of a square section, which are included into the behaviour in transverse tension under the effect of centred local loading, are neither registered, standardised, nor limited, but they can vary within a significant range. Norms [2–4, 10] do not regulate the height or thickness of the concrete elements for local compression calculations.

While calculating the effect of local loading, evenly distributed over the area A_{c0} (Figure 1), the concentrated force of resistance $F_{Rdu,p}$ in pursuance of the valid norms [5], is established using the formula:

$$F_{Rdu} = A_{c0} f_{cd} \sqrt{\frac{A_{c1}}{A_{c0}}} \leq 3 f_{cd} A_{c0} \tag{3}$$

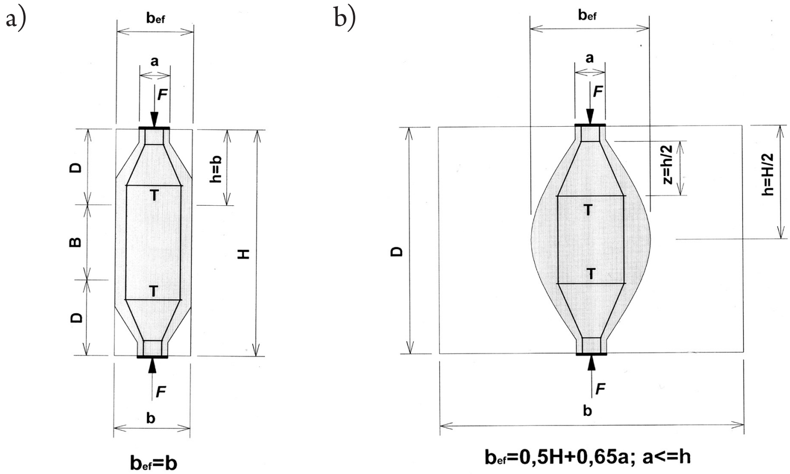
where: A_{c0} – is the area of loading; A_{c1} – is the maximal calculated area of distribution; f_{cd} – is the calculated value of concrete compression strength.

As we see, norms [5] in formula (2) continue to apply the approach to power F_{Rdu} through the calculated value of concrete compression strength, as the case is with norms [2–4], but they take into account the height *h* of the distribution of loading, and other additional new parameters and their limitations are introduced.



h≥(b$_2$-b$_1$); h≥(d$_2$-d$_1$)

Fig. 1. Calculated distribution for partially loaded areas



B – area without discontinuity (homogeneous); D – area with discontinuity (heterogeneous)

Fig. 2. Parameters for determining the transverse tension force *T* in compressed fields of concrete elements for designing the distributed reinforcement:
a – partial discontinuity; b - total discontinuity

The principle of taking crack formation into account is quite empirical. The tension strength *T*, which should provide for the appropriate transverse reinforcement, is taken from the value of the longitudinal force *F* according to the geometric parameters $a=b_1$ and $b \geq b_2$ or d_2 (same type designation in Fig. 1 and Fig. 2).

For areas with partial distribution $b \leq H/2$ (Fig. 2, a), use the formula:

$$T = 0{,}25 \times \left(\frac{b-a}{b} \right) \times F; \tag{4}$$

For areas with partial distribution $b > H/2$ (Fig. 2, b), use the formula:

$$T = 0{,}25 \times \left(1 - 0{,}7 \frac{a}{h} \right) \times F. \tag{5}$$

3. Purpose of the study and research tasks

As we see from the similar calculation designs of bearing listed in normative documents [2–4] and the design for partially loaded areas of bearing under the valid norms [5], they have relation to their calculated approach, when designing concrete elements. During the compression exerted by longitudinal forces, this especially refers to the assessment of characteristics of stage-wise and boundary deformation, crack formation and kinematics of crack formation, as well as to the destruction of concrete due to transverse tension in the holder around the area of loading.

The purpose of the present study is to identify the main factors that distinguish between traditional empirical approaches to calculation designs for partially loaded areas and the experimental nature of the distribution of tensile deformation, micro-crack formation and destruction of concrete of the holder around the area of loading.

The carried-out study aimed at identifying appropriate transverse tension deformation of concrete along the perimeter of side cube faces during the formation of micro- and macro-cracks to the destruction of various levels of loading on the partially loaded area in the volumetric concrete elements in the form of cubes with edges measuring 300 mm.

4. The results of the study

According to the set task, let us check the features of the behaviour for boundary conditions adopted in design [5] of the calculated distribution for partially loaded areas and the thereto corresponding formula (2).

It is necessary to observe the calculated boundary conditions:

- the relationship of the area of base A_{c1} to the upper area A_{c0} of the partially loaded area should be $A_{c1}/A_{c0} \geq 9$;
- the minimum height h should be no more than the double maximum amount of the area the loading area A_{c0}-$h \geq 2 \times b_2$ or $h \geq 2 \times d_2$.

Such conditions will accommodate the testing samples in the form of a cube (Fig. 3).

The manufactured concrete cubes (K1-3×3, K2-3×3) with edge dimensions of 300 mm (Fig. 3) are used to establish the influence of the nature of the tension stress distribution along the lateral faces of the volumetric concrete elements on the nature of their micro and macro-crack formation and destruction. The cubes are made of heavy concrete of class C18/22,5 (compression strength: the medium strength is $f_{cm.cube}$=28,5MPa; the characteristic strength is $f_{ck.cube}$=22,5MPa; calculated strength is f_{cd} = 13MPa).

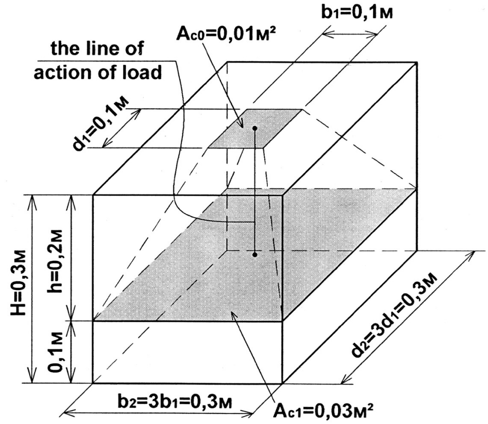
The cubes were loaded from above applying uniformly distributed loading q_{loc} within a limited area A_{c0}=0,1×0,1=0,01 m^2. The bottom face of the cube A_{c1}=0,3×0,3=0,09 m^2 was lying tightly on a hard press plate (Fig. 4, 5).

While testing the cubes, the tensile strain was measured along their perimeter at three levels of 0,05 m, 0,15 m, and 0,25 m from the bottom face. All samples were tested under the application of centred loading. The loading was applied stage-wise up to the expected destructive force.

The characteristics and the analysis of the tested concrete cubes, applying methods [1] and [5] respectively, are shown in Table 1 and 2.

According to calculation methods [5], it is not quite clear how to assume the assured calculated value, which is less than the boundary value, of the component of formula (3). The boundary value is 3/2,08=1,442 times bigger, than the average experimental value.

The fact that the destruction of the tested samples resulted not only due to bearing, but due to the combination of compression stresses (deformations) and bearing and splitting tension is evidenced not only by concrete horizontal tensile deformations measured in the course of testing, but also by the nature of crack formations during the destruction of tested samples (Fig. 4, 5).



$$h \geq (b_2 - b_1);\ h \geq (d_2 - d_1)$$

Fig. 3. Calculated distribution along the height h for the partially loaded area A_{s0} that corresponds to the boundary conditions of the calculated design shown in Fig. 1 and to boundary limit of formula (2)

a) 

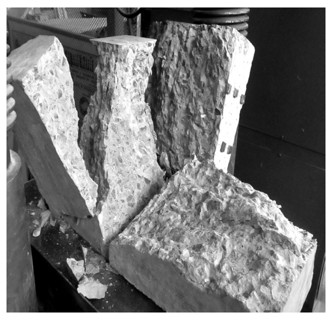
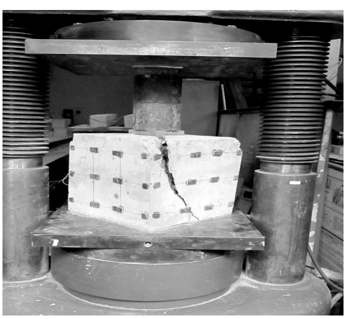
b) 

Fig. 4. The nature of crack formation (a) and destruction (b) under locally applied loading on the concrete cube K1-3×3 (A_{c0}=0,01 m² A_{c1}=0,0425m²)

a) 

b) 

Fig. 5. The nature of crack formation (a) and destruction (b) under locally applied loading on the concrete cube K2-3×3 (A_{c0}=0,01 m² A_{c1}=0,0441 m²)

Table 1. Typical data for the concrete cubes when using methods [1]

Mark sample	$l=b=h$, m	$A_{loc.1}$, m^2	$A_{loc.2}$, m^2	$\sqrt[3]{Aloc2/Aloc_1}$		F_u, kN	$R_{m.cube}$, MPa	The calculated value		$N_{m.cub}$, kN	$N_{b.ultum}$, kN	N/F_u
				$\varphi_{b.f.}$	$\varphi_{b.ultum}$			$N_{b.f}$, kN	$N_{b.ultum}$, kN			
K1-3×3	0,3	0,01	0,09	2,08<	2,5	800	28,5	270,4	325	592	713	0,338
K2-3×3	0,3	0,01	0,09	2,08<	2,5	900	28,5	270,4	325	592	713	0,338
Heavy concrete class: B 22,5 [5] (compression strength: the medium value is $R_{m.cube}$=28,5 MPa; the normative prism value is $R_{b.ser}$=16,75 MPa; the calculated value is R_b=13 MPa; the value of tension is $R_{bt.ser}$=1,5 MPa; R_{bt} =0,975 MPa).												

Table 2. Typical data for the concrete cubes when using methods [5]

Mark sample	$l=b=h$, m	A_{c0}, m^2	A_{c1}, m^2	$\sqrt{Ac1/Ac0}$		F_u, kN	$f_{cm.cube}$, MPa	The behaviour value		$F_{Rdu.c.f}$, kN	$F_{Rdu.ult}$, kN	$F_{Rdu.f}/F_u$
				fact	*ultum*			$F_{Rdu.f}$ *fact*, kN	$F_{Rdu.(3)}$ *ultum.*, kN			
K1-3×3	0,3	0,01	0,0425	2,06<	3	800	28,5	268	390	588	855	0,335
K2-3×3	0,3	0,01	0,0441	2,10<	3	900	28,5	273	390	598	855	0,303
Heavy concrete class: C18/22,5 [4] (compression strength: the medium value is $R_{m.cube}$=28,5 MPa; the characteristic value – $f_{ck.cube}$=22,5 MPa; the calculated value is f_{cd}=13 MPa.												

The actual nature of the distribution of tension strain at three levels of height h and along the perimeter of the lateral faces of cubes of the partially loaded area is shown in Figures 6, 7, and 8.

It should be noted that while testing the samples for a central application of force onto a fixed area, uneven distribution of horizontal tension strain $\varepsilon_{bt}\times10^{-5}$ according to the perimeters at three levels along the height h (Fig. 6, 7, and 8) is observed.

Tension strain values at the top - first level of the lateral faces in all tested samples were bigger, than at the second and third levels closer to their lower carrying face (Fig. 10, 11).

The diagrams of unit strains of concrete under the application of the die block according to the stress under it (Fig. 11) show that the curve has three areas of stress change σ under the die block from the corresponding forces $F_{Rdu.i}$ (N_i): the first one – from 0 MPa to 30 MPa, the second one – from 30 MPa to 80 MPa and the third one – from 80 MPa to F_u MPa, which describe the transitional stage-wise phases of the concrete stress-deformed state.

The comparison of the two curves of dependence (Fig. 11) of the stress under the side block on the unit strain of the pushing pyramids with the equal height (the first dependence at $h=H=0,3$ m and the second dependence at the unit height $h=2b_1=0,2$ m) showed that, compared with the full diagram of concrete compression according to the characteristic parameters, the first curve corresponds better to the full concrete compression diagram, graphed using methods [1].

The stress values σ»30 MPa in the typical transition point between the first and the second areas describes the beginning of the micro-crack formation in the concrete of cubes and is characterised by unit strains of $\varepsilon_{bt}=10\times10^{-5}$ (Fig. 6). The stress value of σ»30 MPa, thereby, coincides practically with the average stress calculated value according to data [1] $\sigma_1=N/A_{loc.1}=270,4/0,01=27,04$ MPa (Table. 1) and the processing of experimental data according to formula (2) of norms [5] $\sigma_2=\sigma_1=F_{Rdu}/A_{c0}=(268+273)/2/0,01=27,05$ MPa (Table 2).

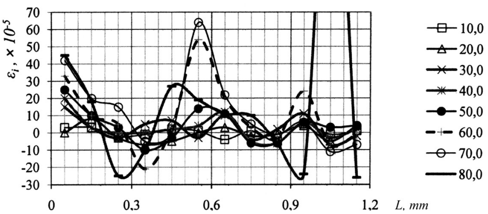


Fig. 6. Unit strain along the perimeter of a cube at the level of 0,25 m from its base

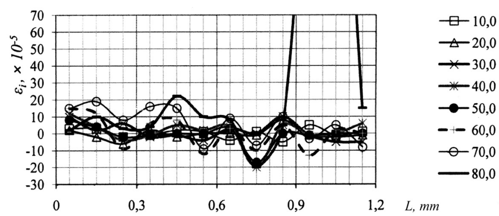


Fig. 7. Unit strain along the perimeter of the cube at the level of 0,15 m from its base

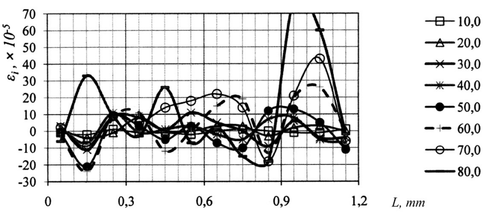


Fig. 8. Unit strain the perimeter of the cube at the level of 0,05 m from its base

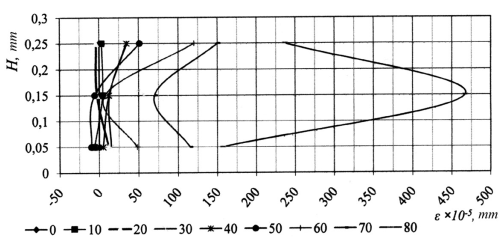


Fig. 9. The total strain along the perimeter of the cube at three levels from its base (0,25 m, 0,15 m, and 0,05 m)

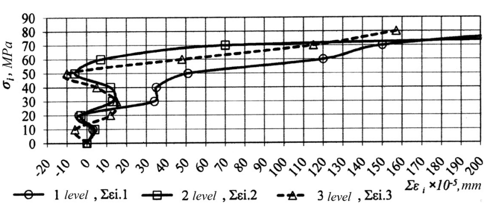


Fig. 10. Dependence of total strain along the perimeter of the cube at three levels from its base (0,25 m, 0,15 m, and 0,05 m) from the stresses under the die

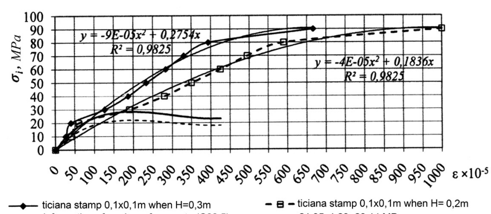


Fig. 11. Dependence of stress under the on the relative unit strain of the pushing pyramid with the cube height of $H=0,3$ m, and the relative height of $h=2b_1=0,2$m compared with the full concrete compression diagram

The stress value σ»80 MPa in the typical transition point between the second and the third areas describes the beginning of the macro-crack formation in concrete cubes and is characterised by unit strains of $\varepsilon_{bt}=400\times10^{-5}$ (Fig. 6) [1]. The stress value of σ»80 MPa, thereby, is practically approaching the boundary values, both according to norms [3] $\sigma_{1,u}=N_{b.ultum}/A_{loc.1}=713/0{,}01=71{,}3$ MPa (Table 1) and according to norms [5] $\sigma_2=\sigma_{1,u}=F_{Rdu.ult}/A_{c0}=855/0{,}01=85{,}5$ MPa (Table 2).

The uniform transmission of bearing loading on the top face of the concrete samples increases, without doubt, their actual carrying capacity, but the values of destructive loading, obtained during the tests, can be considered somewhat bigger compared with those, which may be in natural structures. This is due primarily to the fact that during the study, a rather high rigidity base was used (bottom steel press plate) under the bottom face of the cubes, which is difficult to achieve under actual conditions of construction.

5. Conclusions

With reference to the nature of the destruction of the tested concrete cubes under the effect of local vertical loading along their geometrical axis, the following was revealed:

- the processed experimental data on concrete cube samples, tested for the effect of local loading, revealed, according to the assessment of the concrete stress-strain state through the fixed levels of tensile strain, a stable value of the calculated concentrated forces of the levels of crack formation and destruction of the cube samples;
- destruction is due to bearing-cracking of concrete, starting from the top face under the fixed area of the partially loaded area, where, due the vertical and transverse strain, the volume of the incomplete pushing pyramid increases, from which pyramid the longitudinal crack formation and splitting of the cube body are running;
- the bottom face of the incomplete pushing pyramid, which bottom face is running along the full height of the cube, covers an area on the lower bearing face of the cube, which is less than the area of the cube;
- the analysis of the stress curves under the die block depending on the unit strains of the pushing pyramids equal to the height with the full diagram of the concrete compression strain made it possible to determine that the transition of the cube concrete to the micro-crack formation is carried out at the unit strain values of $\varepsilon_{bt}=10\times10^{-5}$, and to the macro-crack formation and gradual physical destruction is carried out at the relative boundary deformation values of $\varepsilon_{bt}=400\times10^{-5}$ according to the characteristic parameters of the full concrete compression diagram;
- the results of comparing the test data with the data of the calculation using the methods of the old Construction Norms and Regulations, SNIP [3] and the current standard DSTU [4] showed that the derived calculated and behaviour values of centred forces, listed in Tables 1 and 2, are practically similar $N=F_{Rdu}=270$ kN;
- as to calculation methods [5], it is not completely clear, how to take the assured, lower value for the boundary the calculated value of the component   of formula (2), or

should the boundary value be taken right away. Then, in view of the data obtained during testing the cubes, the relationship of concentrated forces is N/F_{Rdu}=270/390=0.69 (calculated forces [3] to behaviour forces [5]). Other data are listed in Tables 1 and 2.

- the approach to calculating the effect of local vertical loading on the samples of the dealt with type should be taken account of in [5] taking into consideration the nature of their destruction and the hardness of the base under their bottom face using the reduction factor of their behaviour conditions.

The nature of the crack formation, while changing the stress-strain state in flat concrete elements under symmetrical loading in the conditions of changing their height with other parameters remaining constant, is shown in [6].

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