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DEVELOPMENT OF A PROCEDURE FOR THE EVALUATION OF THE STRESSED-DEFORMED STATE OF PIPE-CONCRETE ELEMENTS THAT ARE STRETCHED OFF-CENTER

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Розроблено методику оцінки напружено-деформованого стану позацентрово розтягнутих трубобетонних елементів суцільного поперечного перерізу. Отримано теоретичні залежності. Визначено значення напружень і деформацій в оболонці та бетонному ядрі залежно від геометричних характеристик і фізико-механічних властивостей матеріалів. Ураховується об'ємно-напружений стан бетонного осердя

Ключові слова: трубобетон, напружено-деформований стан, позацентровий розтяг, теорія пружності, граничний стан

Разработана методика оценки напряженно-деформированного состояния внецентренно растянутых трубобетонных элементов сплошного поперечного сечения. Получены теоретические зависимости. Определены значения напряжений і деформаций в оболочке и бетонном ядре в зависимости от геометрических характеристик и физико-механических свойств материалов. Учитывается объемно-напряженное состояние бетонного ядра

Ключевые слова: трубобетон, напряженно-деформированное состояние, внецентренное растяжение, теория упругости, предельное состояние

1. Introduction

There are several different stages of the stressed-strained state in the elements with indirect reinforcement, as well as in other structures, from the onset of loading up until destruction. These states are characterized by different magnitude and character of deformations and stresses.

Based on the studies already conducted [1–3], when characterizing the boundary state of the elements with indirect reinforcement, it is possible to argue that at low loads the shell deforms elastically while the concrete starts to exhibit plastic deformations. With an increase in the load, cracks form in concrete, the lateral pressure between the concrete and the shell increases. Upon further increase in loading, longitudinal stresses in the shell reach yield point, and there occur cracks in the concrete core in the planes, perpendicular to the plane of applied effort. Under this state, an element with indirect reinforcement is capable of receiving growing load. The boundary condition is determined by the magnitude of critical deformations. In the case of pipe-concrete, limit deformations imply yield point of the steel shell.

During operation of stretched elements made of pipe-concrete, there may appear conditions under which a structure works in the elastic or plastic stage. At present, there are estimations of the stressed-strained state of pipe-concrete that works on compression, bending and central elongation; however, evaluation of the stressed-strained state of pipe-concrete on a non-center stretch is lacking. The implementation of effective pipe-concrete structures in building industry necessitates a more detailed study into the features of work under load. Results of the study could be used in designing the structures in which pipe-concrete elements work under stretching, in particular, the through columns, arches, trusses, etc. Thus, the task of the estimation of the stressed-strained state of pipe-concrete that is stretched off-center appears relevant.

2. Literature review and problem statement

It was established by experimental data [4] that in the pipe-concrete elements the concrete core works at stretching jointly with a pipe-shell. In this case, with an increase in the level of concrete load, complex stressed-strained state in the steel and concrete constantly changes [5]. The magnitude of stress is most significantly affected by the reinforcement coefficient and mechanical characteristics of materials [1] (deformation module and Poisson ratio). Characteristics *E* and ν are not constant magnitudesn. With an increase in loading, elastic characteristics change magnitude.

Articles [6, 7] described theoretically substantiated procedures for studying the operation of pipe-concrete structures under load. Concrete is characterized by a nonlinear dependence between stresss and deformations at all levels of loading [8]. Curvilinear character of deformation dependence on stresses is explained by the development of fracture of concrete at the micro level [9]. The work of steel that the shell is made of is not confined to the work in the elastic stage as well [10].

Description of the stressed-strained state of structures whose material deforms nonlinearly in a general case runs into significant mathematical complexities [11]. For the elements with indirect reinforcement and, specifically, in pipe-concrete elements, these circumstances are complicated by the concrete being exposed to the conditions of the triaxial stressed state [12]. This manifests itself regardless of the material of the outer shell [2, 13]. Most discussions addressed the issue of the joint work of the core and the shell at the boundary of contact [3]. In addition, still unresolved up to now is the issue of defining a single criterion for the strength of concrete core in the composition of pipe-concrete [14].

3. Research goal and objectives

The goal of present study is the development of a procedure for evaluating the stressed-deformed state of pipe-concrete elements that are stretched off-center from the onset of loading and up to their reaching the boundary state.

To accomplish the formulated goal, the following tasks have been set:

– based on the apparatus of the theory of mechanics of the deformed body, to develop an algorithm of determining the components of the stressed-deformed state of pipe-concrete elements that are stretched off-center;

– to apply the developed algorithm for determining the bearing capacity of pipe-concrete elements that are stretched off-center and to compare with experimental data.

4. Procedure for the estimation of the stressed-deformed state of pipe-concrete elements at stretching

In order to solve the set task, by employing the mathematical theory of elasticity we obtained a solution for the elastic stage of work of the stretched element, based on paper [12]. The stressed-deformed state of pipe-concrete elements that are stretched off-center is the sum of the stressed states of the element stretched centrally [15] and of the bent element. In this case, the latter works under conditions of pure bending.

The following prerequisites underlie the procedure:

– concrete is considered to be an isotropic material with elastic plasticity;

– a linear dependence is considered to exist between stresses and deformations;

– the hypothesis of flat cross-sections is considered to hold;

– geometrical and physical characteristics of the utilized materials lengthwise of the element are accepted to be constant;

– it is considered that the pipe and the concrete deform jointly;

– a two-digit stress epure in the first variant of the boundary condition on strength of the concrete and the pipe in the compacted and stretched zones has the shape of a triangle, while in the second variant – the shape of a rectangle;

– the static conditions are maintained;

– the shape of the bending of the element axis is accepted to be flat and corresponds to a sinusoid;

– concrete in the stretched zone is not taken into account in the work of the cross section; concrete of the compacted part of the cross-section is under conditions of volumetric compression.

We shall consider the stressed-deformed state of pipe-concrete elements working under pure bending for the two variants of boundary condition by strength.

In the first case, deformations in the most compressed fibers of cross-section reach values that match yield point of steel of the pipe. For this purpose, we shall split the section into three regions (Fig. 1).

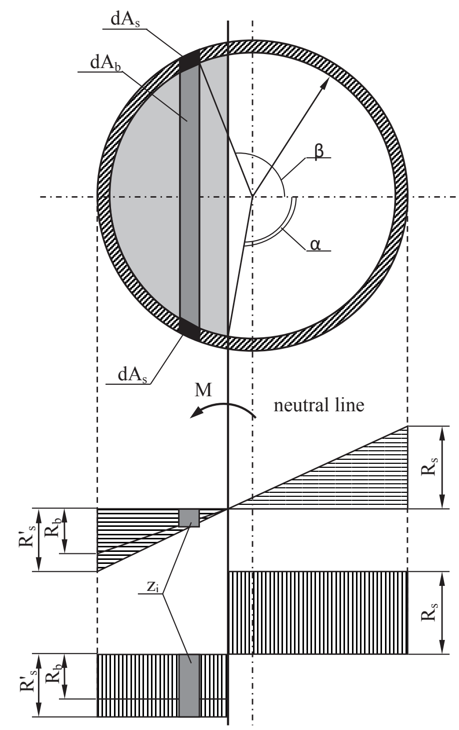

Fig. 1. Estimated diagram of the cross section of a pipe-concrete element that works under bending

In line with the rule of superposition, equally acting internal efforts of the compressed and stretched zones of cross section is the sum of internal efforts of separate regions, and the moments are the sum of internal moments. Mathematical essence of internal effort for each region separately is the volume of some spatial figure. Moment is determined as the product of the corresponding volume V_z on the shoulder (the distance from the center of gravity of the body of volume V_z to the point of coordinate origin).

For section 1 (compressed concrete region), we obtain:

$$N_1 = \frac{2r_s^2\sigma_z^{b\prime}}{1+\cos\alpha}\left[\frac{(\pi-\alpha)\cos\alpha}{2}+\frac{\cos^2\alpha\sin\alpha}{2}+\frac{\sin^3\alpha}{3}\right]; \quad (1)$$

$$M_1=\frac{2r_s^3\sigma_z^{b\prime}}{1+\cos\alpha}\left(\frac{\cos\alpha\sin^3\alpha}{3}+\frac{\pi-\alpha}{8}+\frac{\sin 4\alpha}{32}\right). \quad (2)$$

For section 2 (compressed pipe-shell region), we obtain:

$$N_2=\frac{2r_s\delta_s\sigma_z^{s\prime}}{1+\cos\alpha}\left[(\pi-\alpha)\cos\alpha+\sin\alpha\right]; \quad (3)$$

$$M_2=\frac{2r_s^2\delta_s\sigma_z^{s\prime}}{1+\cos\alpha}\left(\cos\alpha\sin\alpha+\frac{\pi+\alpha}{2}-\frac{\sin 2\alpha}{4}\right). \quad (4)$$

For section 3 (stretched pipe-shell region), we obtain:

$$N_3=\frac{2r_s\delta_s\sigma_z^{s}}{1-\cos\alpha}(\sin\alpha-\alpha\cos\alpha); \quad (5)$$

$$M_3=\frac{2r_s^2\delta_s\sigma_z^{s}}{1-\cos\alpha}\left(\frac{\alpha}{2}+\frac{\sin 2\alpha}{4}-\cos\alpha\sin\alpha\right). \quad (6)$$

We shall write the static conditions $\sum N_z=0,\ \sum M_z=0$ in the following form:

$$\sum N_z=N_1+N_2-N_3=0; \quad (7)$$

$$\sum M_z=M_1+M_2+M_3-M=0. \quad (8)$$

By substituting equations (1), (2) and (3) in (4), we shall obtain:

$$\sum N_z=2r_s\left[\frac{r_s\sigma_z^{b\prime}\omega_1}{1+\cos\alpha}+\delta_s\left(\frac{\sigma_z^{s\prime}}{1+\cos\alpha}\left[(\pi-\alpha)\cos\alpha+\sin\alpha\right]-\frac{\sigma_z^{s}}{1-\cos\alpha}(\sin\alpha-\alpha\cos\alpha)\right)\right]=0; \quad (9)$$

$$\sum M_z=2r_s^2\left[\frac{r_s\sigma_z^{b\prime}\omega_2}{1+\cos\alpha}+\delta_s\left(\frac{\sigma_z^{s\prime}}{1+\cos\alpha}\left(\cos\alpha\sin\alpha+\frac{\pi+\alpha}{2}-\frac{\sin 2\alpha}{4}\right)+\frac{\sigma_z^{s}}{1-\cos\alpha}\left(\frac{\alpha}{2}+\frac{\sin 2\alpha}{4}-\cos\alpha\sin\alpha\right)\right)\right]=M, \quad (10)$$

where σ_z^s is the stress in the stretched zone of the pipe; $\sigma_z^{b\prime}$, $\sigma_z^{s\prime}$ are the stresses in the compressed zone of the concrete and the pipe-shell;

$$\omega_1=\frac{(\pi-\alpha)\cos\alpha}{2}+\frac{\cos^2\alpha\sin\alpha}{2}+\frac{\sin^3\alpha}{3}; \quad (11)$$

$$\omega_2=\frac{\cos\alpha\sin^3\alpha}{3}+\frac{\pi-\alpha}{8}+\frac{\sin 4\alpha}{32}. \quad (12)$$

Using the equation of compatibility of deformations, it is possible to write:

$$\sigma_z^{b\prime}=n\sigma_z^{s\prime}. \quad (13)$$

Fig. 1 shows that σ_z^s can be expressed through $\sigma_z^{s\prime}$ in the following way:

$$\frac{\sigma_z^{s\prime}}{r_s+r_s\cos\alpha}=\frac{\sigma_z^{s}}{r_s-r_s\cos\alpha}; \quad (14)$$

$$\sigma_z^{s}=\frac{\sigma_z^{s\prime}(1-\cos\alpha)}{1+\cos\alpha}. \quad (15)$$

Substitute equation (15) in equations (9) and (10), we shall obtain:

$$\sum N_z=\frac{2r_s\sigma_z^{s\prime}}{1+\cos\alpha}\left[nr_s\omega_1+\delta_s\pi\cos\alpha\right]=0; \quad (16)$$

$$\sum M_z=\frac{2r_s^2\sigma_z^{s\prime}}{1+\cos\alpha}\left(nr_s\omega_2+\delta_s\frac{\pi+2\alpha}{2}\right)=M. \quad (17)$$

We determine $\sigma_z^{s\prime}$ from equation (17):

$$\sigma_z^{s\prime}=\frac{Ne(1+\cos\alpha)}{2r_s^2\left(nr_s\omega_2+\delta_s\frac{\pi+2\alpha}{2}\right)}. \quad (18)$$

We determine angle α from equation (16):

$$\cos\alpha=-\frac{nr_s\omega_1}{\pi\delta_s}. \quad (19)$$

In the second case, the cross-section of a pipe-concrete element is divided into three regions, similar to that in the first variant of boundary condition.

For section 1 (compressed concrete region), we obtain:

$$N_1=2r_s^2\sigma_z^{b\prime}\left(\frac{1+\cos^3\alpha}{3}\right); \quad (20)$$

$$M_1=2r_s^3\sigma_z^{b}\left(\sin\alpha-\frac{\sin 4\alpha}{4}\right). \quad (21)$$

For section 2 (compressed pipe-shell region), we obtain:

$$N_2=2r_s\delta_s\sigma_z^{s\prime}(\pi-\alpha); \quad (22)$$

$$M_2=2r_s^2\delta_s\sigma_z^{s\prime}\sin\alpha. \quad (23)$$

For section 3 (stretched pipe-shell region), we obtain:

$$N_3=2r_s\delta_s\sigma_z^{s}\alpha; \quad (24)$$

$$M_3=2r_s^2\delta_s\sigma_z^{s}\sin\alpha. \quad (25)$$

We substitute equations (20)–(25) in the static conditions (7), (8), and we obtain:

$$\sum N_z=2r_s^2\sigma_z^{b\prime}\left(\frac{1+\cos^3\alpha}{3}\right)+2r_s\delta_s\sigma_z^{s\prime}(\pi-\alpha)-2r_s\delta_s\sigma_z^{s}\alpha=0; \quad (26)$$

$$\sum M_z = 2r_s^3\sigma_z^b\left(\sin\alpha - \frac{\sin 4\alpha}{4}\right) +$$

$$+2r_s^2\delta_s\sigma_z^{s\prime}\sin\alpha + 2r_s^2\delta_s\sigma_z^s\sin\alpha = M; \quad (27)$$

where

$$\omega_3 = \frac{1+\cos^3\alpha}{3}; \quad (28)$$

$$\omega_4 = \sin\alpha - \frac{\sin 4\alpha}{4}. \quad (29)$$

By using the equations of compatibility of deformations, as well as in line with Fig. 1, σ_z^s, $\sigma_z^{s\prime}$, σ_z^b can be expressed through $\sigma_z^{s\prime}$:

$$\sigma_z^s = \sigma_z^{s\prime}. \quad (30)$$

Substitute expression (13) and (30) in equations (26) and (27), we shall obtain:

$$\sum N_z = 2r_s\sigma_z^{s\prime}\left[nr_s\omega_3 + \delta_s(\pi - 2\alpha)\right] = 0; \quad (31)$$

$$\sum M_z = 2r_s^2\sigma_z^{s\prime}\left(nr_s\omega_4 + 2\delta_s\sin\alpha\right) = M; \quad (32)$$

$$\sigma_z^{s\prime} = \frac{Ne}{2r_s^2\left(nr_s\omega_4 + 2\delta_s\sin\alpha\right)}. \quad (33)$$

In the case of a two-digit epure stresses at off-center stretching, a neutral line slightly changes its position, which is why we consider angle α to remain unchanged until the destruction, and the value of angle α is determined from (19).

Therefore, stresses and deformations of the pipe-concrete elements that are stretched off-center will equal to:

a) in the most stretched fiber;

– at stage I:

$$\sigma_{z_4}^s = \sigma_{z_1}^s + \sigma_z^s; \quad (34)$$

$$\varepsilon_{z_1}^s = \frac{\sigma_{z_4}^s}{E_s}; \quad (35)$$

– at stage II:

$$\sigma_{z_5}^s = \sigma_{z_3}^s + \sigma_z^s; \quad (36)$$

$$\varepsilon_{z_2}^s = \frac{\sigma_{z_5}^s}{E_s}; \quad (37)$$

b) in the most compressed fiber;

– at stage I:

$$\sigma_{z_4}^{s\,\prime} = \sigma_{z_1}^s + \sigma_z^{s\prime}; \quad (38)$$

$$\varepsilon_{z_1}^{s\,\prime} = \frac{\sigma_{z_4}^{s\,\prime}}{E_s}; \quad (39)$$

– at stage II:

$$\sigma_{z_5}^{s\,\prime} = \sigma_{z_3}^s + \sigma_z^{s\prime}; \quad (40)$$

$$\varepsilon_{z_2}^{s\,\prime} = \frac{\sigma_{z_5}^{s\,\prime}}{E_s}; \quad (41)$$

where

$$\sigma_{z_1}^s = -\frac{N}{\left(nA_b + A_s\right)}; \quad (42)$$

$$\sigma_{z_3}^s = -\frac{N}{A_s}. \quad (43)$$

Thus, we obtained the value of stresses and deformations of the boundary fibers of cross-section at pure bending. The values of stresses and deformations of the appropriate fibers at central stretching is determined by procedure [15]. Complete stressed-deformed state by the transverse cross section of the pipe-concrete element that is stretched off-center is equal to the sum of the stressed-deformed states at axial compression from effort N and pure bend from the bending moment M.

5. Comparison of theoretical and experimental data on the pipe-concrete elements that are stretched off-center

In order to compare with the experimental research, we employed pipe-concrete elements from article [1]. We accepted as a theoretical bearing capacity the magnitude ofstretching effort, which matched the occurrence in the most compressed, or stretched, fibers of the estimated cross section of deformation of yield strength of the steel of a pipe-shell. Comparison of the theoretical and experimental bearing capacity is given in Table 1.

Table 1

Comparison of the experimental and theoretical values of bearing capacity

Series of a sample	Eccentricity, mm	Bearing capacity, kN		Differ-ence, %
		Experimental	Theoretical	
TR-1	50	204	214	–5.1
TR-2	50	144	154	–7.0
TR-3	25	221	241	–9.1
TR-3	50	149	159	–7.0
TR-4	50	112	122	–9.0
TB-11	50	224	244	–9.3
TB-21	50	158	178	–13.2
TB-31	25	243	263	–8.3
TB-31	50	164	174	–6.5
TB-32	50	164	173	–6.0
TB-33	50	164	174	–6.2
TB-41	50	124	134	–8.2
Average, %				–7.91

Fig. 2 shows a characteristic diagram of the change in the stressed-deformed state of pipe-concrete elements that are stretched off-center.

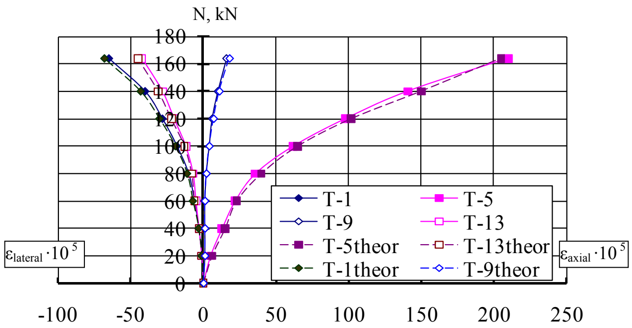

Fig. 2. Comparison of theoretical and experimental dependences of longitudinal and transverse deformations on the magnitude of loading by off-center stretching with an eccentricity of *e*=50 mm for a sample of the series TB-31

An analysis of the change in the stressed-deformed state of the pipe-concrete elements that are stretched off-center revealed a common character of deformation for all the examined samples. Thus, the character of dependence N–ε at the initial stage displays an almost straight shape. Noticeable increase in the longitudinal and transverse deformations from the effort is observed at ε_{axial}=(50–80)·10^{-5} and $\varepsilon_{lateral}$=(10–25)·10^{-5}. At this point, the curve N–ε has a pronounced curvilinear character. At reaching ε_{axial}=(200–220)·10^{-5}, which corresponds to yield point of steel of the pipe, there is an increase in $\varepsilon_{lateral}$. In the longitudinal and transverse directions the growth of deformations occurs in proportion, while the dependence is of a curvilinear character. Noteworthy is the fact that almost all the epures of deformation are curvilinear, that is, the hypothesis on the flat cross sections held.

6. Discussion of results of applying the proposed procedure for estimating bearing capacity of the pipe-concrete elements that are stretched off-center

The obtained functional dependences make it possible to establish the magnitudes of stresses and deformations in the pipe-shell and in the concrete of pipe-concrete elements that are stretched off-center depending on geometrical characteristics and physical-mechanical properties of the element materials. The procedure takes into account the elastic stage of work of the materials considering the volumetrically stressed state and an increase in the loading from zero to destruction. The disadvantage of this procedure is that it does not account for the plastic properties of the applied materials. The benefit of the developed procedure is the proposed simplified method for solving the system of defining equations based on the hypothesis about a joint work of the components of pipe-concrete (steel shell and concrete core) at all stages of loading with an effort that is stretched off-center. This procedure is implemented through a successive solution of separate equations. The existing evaluation procedures of the stressed-deformed state of stretched pipe-concrete elements do not take into account the negative impact of bending moment, which is an additional force factor under conditions of the off-center stretching.

The proposed procedure of evaluation of the stressed-deformed state males it possible to determine with a sufficient accuracy the bearing capacity of pipe-concrete elements that are stretched off-center with different geometrical parameters and mechanical properties. Results of the calculation of bearing capacity satisfactorily match experimental data.

In order to increase the accuracy of theoretical results of the proposed procedure, it is necessary to improve it. Failing to consider plastic properties of steel and concrete has led to theoretical overestimation of the bearing capacity of pipe-concrete elements that are stretched off-center in comparison with experimental data. Further development of the proposed methodology should take into account the development of plastic properties of steel and concrete.

7. Conclusions

1. We developed a procedure for evaluating the stressed-strained state of elements that are stretched off-center, which make it possible to determine the value of bearing capacity, stresses and deformations in the shell and the concrete core depending on geometrical characteristics and physical-mechanical properties of the materials. Its special feature is in the fact that in order to to determine components of the stressed-strained state, the system of equations is solved not by selecting a particular function but rather by consistent solution of separate equations. It is shown that the procedure for determining components of the stressed-deformed state of pipe-concrete elements that are stretched off-center is significantly simplified due to this special feature.

2. We compared experimental values of the bearing capacity of pipe-concrete elements that are stretched off-center with theoretical values that were calculated by the developed procedure. Analysis of the results demonstrates that deviations were equal to 7.9 %. Such a convergence of comparison results confirms the hypothesis about joint work of the steel shell and the concrete core up until the moment when a pipe-concrete element that is stretched off-center reaches maximal bearing capacity.

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