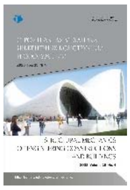
2023. 19(4). 410–418

СТРОИТЕЛЬНАЯ МЕХАНИКА ИНЖЕНЕРНЫХ КОНСТРУКЦИЙ И СООРУЖЕНИЙ

STRUCTURAL MECHANICS OF ENGINEERING CONSTRUCTIONS AND BUILDINGS

ISSN 1815-5235 (Print), 2587-8700 (Online)

HTTP://JOURNALS.RUDN.RU/STRUCTURAL-MECHANICS



ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ

EXPERIMENTAL RESEARCH

DOI: 10.22363/1815-5235-2023-19-4-410-418
EDN: VPVGFF
UDC 624.044.2

RESEARCH ARTICLE / НАУЧНАЯ СТАТЬЯ

Experimental and analytical models of longitudinal deformation in pipe-concrete specimens with small cross-sections

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Article history
Received: April 28, 2023
Revised: August 7, 2023
Accepted: August 16, 2023

Acknowledgements
The work was carried out within the state assignment for fundamental scientific research in 2021–2023 under the project No. 0030-2021-0025.

For citation
Khazov P.A., Erofeev V.I., Nikitina E.A., Pomazov A.P. Experimental and analytical models of longitudinal deformation in pipe-concrete specimens with small cross-sections. *Structural Mechanics of Engineering Constructions and Buildings.* 2023;19(4):410–418. http://doi.org/10.22363/1815-5235-2023-19-4-410-418

Abstract. The results of experimental studies of deformation problems in pipe-concrete specimens with small cross sections are provided and analyzed. The stress-strain state of a steel pipe and a pipe filled with concrete is studied and compared. Experimental determination of the dependencies between axial load and deformations of pipe-concrete and steel bars, as well as evaluation of concrete's and steel pipe's contribution to the total load-bearing capacity of the composite section are provided. Tests were carried out for short pipe-concrete specimens with the pipe dimensions equal to 60x2, 76x3 and 102x3.5, as well as for hollow steel pipes with the corresponding dimensions. The diagrams of deformation were obtained basing on the experimental results. The deformation of the pipe-concrete element under central compression occurs in proportion to the deformation of a hollow steel element with the same diameter, that made it possible to evaluate the contribution of concrete to the work of the pipe-concrete cross-section, which turned out to be constant at each stage of deformation. A methodology has been proposed that enables to describe analytically the deformability of pipe-concrete elements under axial compression by means of the analytical model based on the experimental data.

Keywords: piped concrete, experimental studies, small-sized sections, axial compression, triaxial compression, bearing capacity, stress-strain state, deformability, mathematical model, analytical model

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Экспериментальные и аналитические модели продольного деформирования трубобетонных образцов малогабаритных сечений

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История статьи
Поступила в редакцию: 28 апреля 2023 г.
Доработана: 7 августа 2023 г.
Принята к публикации: 16 августа 2023 г.

Благодарности
Работа выполнена в рамках государственного задания на фундаментальные научные исследования на 2021–2023 годы по теме № 0030-2021-0025.

Для цитирования
Khazov P.A., Erofeev V.I., Nikitina E.A., Pomazov A.P. Experimental and analytical models of longitudinal deformation in pipe-concrete specimens with small cross-sections // Строительная механика инженерных конструкций и сооружений. 2023. Т. 19. № 4. С. 410–418. http:// doi.org/10.22363/1815-5235-2023-19-4-410-418

Аннотация. Приводятся и анализируются результаты экспериментальных исследований вопросов деформирования трубобетонных образцов малогабаритных сечений. Исследуется и сравнивается напряженно-деформированное состояние стальной трубы и трубы, заполненной бетоном. Приводятся экспериментальное определение зависимостей между осевой нагрузкой и деформациями трубобетонных и стальных стержней, а также оценка вклада бетона и стальной трубы в общую несущую способность составного сечения. Испытания проведены для коротких трубобетонных образцов с размерами трубы 60×2, 76×3 и 102×3,5, а также полых стальных труб с соответствующими размерами. По результатам экспериментов построены диаграммы деформирования. Деформация трубобетонного элемента при центральном сжатии происходит пропорционально деформации полого стального элемента того же диаметра, что позволило оценить вклад бетона в работу трубобетонного сечения, который оказался постоянным на каждом этапе деформирования. Предложена методика, позволяющая аналитически описать деформативность трубобетонных элементов при центральном сжатии при помощи аналитической модели, основанной на экспериментальных данных.

Ключевые слова: трубобетон, экспериментальные исследования, малогабаритные сечения, осевое сжатие, трехосное сжатие, несущая способность, напряженно-деформированное состояние, деформативность, математическая модель, аналитическая модель

1. Introduction

One of interesting engineering solutions is the use of steel-concrete structures in construction, which, unlike classic reinforced concrete, use steel not only as a reinforcing material, but also as a full-fledged load-bearing element. One of the types of the steel-and-reinforced concrete structures is piped concrete, consisting of a closed steel pipe into which concrete mixture is specially placed and compacted, resulting in a complex jointed composite structure combining the main advantages of classical steel and reinforced concrete elements, leveling and significantly reducing the impact of their disadvantages.

Many scientists and research groups of the world community have been engaged in the study of strength and stability of pipe-concrete elements. Despite the existence of calculation methods reflected in domestic and foreign regulatory documents, all of them do not allow to objectively describe the stress-strain state of pipe-concrete structures under the action of axial compressive load. Various scientific communities in the last decade conducted experimental [1–8], analytical [9–12] and numerical studies [14–16] in order to determine the bearing capacity

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and deformability of composite structures. Special attention has been paid to numerical and analytical calculations in a nonlinear formulation [17; 18], however, there is no unified engineering methodology capable of describing the stress-strain state of pipe-concrete rods.

Depending on the approach for evaluation of the load-bearing capacity of a pipe-concrete section, two interrelated statements of the problem are conditionally accepted: either the influence of concrete on the increase of the load-bearing capacity of the pipe [15], or the reverse variant is considered, i.e. taking the pipe as a steel shell of a concrete rod [6; 7; 9; 19]. Obviously, pipe-concrete is a composite material with mutual influences of concrete core and a steel shell on each other, and both of the above approaches can be considered as approximated models of work. Dimensional ratios of the steel tube-shell (diameter-to-wall thickness ratio — D/t [2; 12; 20]) or the type of concrete infilling [3] are usually considered as the main factors affecting the strength and strain characteristics of a pipe-concrete structure.

The problem of determining the actual stress-strain state of composite structures made of pipes filled with concrete is being raised by many scientific teams, since the existing design standards underestimate the load-bearing capacity of pipe-concrete, defining it as the sum of the load-bearing capacities of the pipe and the concrete core. For example, articles [9; 20] analyze and compare the existing approaches to determine the ultimate compressive load on pipe-concrete columns. The authors of articles [13; 19] analytically consider the effect of casing by introducing an additional summand, which represents the side pressure at the interface between the pipe and concrete. However, experimental studies show that the nature of deformation of the pipe-concrete rod is more similar to the deformation of a hollow steel pipe, and filling with concrete only enhances the performance of the structure.

In this regard, the authors of this paper propose a methodology that allows describing the deformation process of a pipe-concrete specimen on the basis of the deformational characteristics of a steel pipe and considering the contribution of concrete to the structure operation, which is constant at all stages of deformation, by using of a correcting coefficient.

2. Materials and methods

For conducting the experiment, 12 specimens of 100 mm length were made using steel pipes with the following cross sections: a pipe with a diameter of 60 mm and a wall thickness of 2 mm, a pipe with a diameter of 76 mm and a wall thickness of 3 mm, and a pipe with a diameter of 102 mm and a wall thickness of 3.5 mm. The dimensions of the experimental specimens were taken to exclude the influence of flexibility on the load-bearing capacity of short pipe-concrete rods, i.e. to exclude the loss of stability.

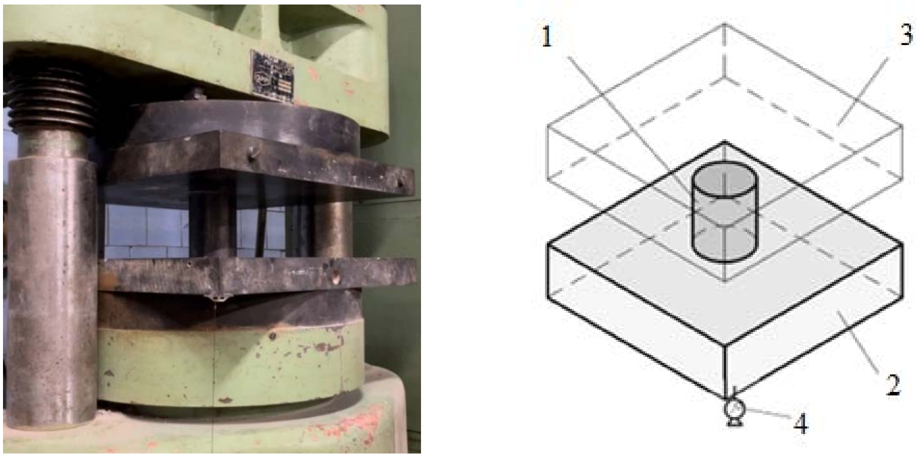
Two pipe-concrete specimens and two hollow specimens, i.e. not filled with concrete, were made from each pipe diameter. Additional reinforcement of the specimens was not used. Conditional marking of the specimens is given in Table 1 for the convenience of processing the results.

Each specimen was tested in the laboratory of the Department of Building Structures of Nizhny Novgorod State University of Architecture and Civil Engineering using a P-125 compression machine with maximum compressive load equal to 1250 kN. In this study, the longitudinal deformations of the samples at each stage of loading with an axial compressive load were determined by the convergence of the pipe-concrete cylinders end sections, for the registration of which the plate convergence indicator had been installed. Figure 1 shows the basic scheme of the experimental equipment for testing specimens of 100 mm in length.

Table 1

Marking of specimens

Specimens mark	Specimen characteristic	Steel pipe dimensions, mm	Diameter of concrete rod crimped by the pipe, mm
P1.1	Hollow Steel Pipe	60×2	—
P1.2			
PC1.1	Pipe filled with concrete (pipe-concrete)	60×2	56
PC1.2			
P2.1	Hollow Steel Pipe	76×3	—
P2.2			
PC2.1	Pipe filled with concrete (pipe-concrete)	76×3	70
PC2.2			
P3.1	Hollow Steel Pipe	102×3.5	—
P3.2			
PC3.1	Pipe filled with concrete (pip-concrete)	102×3.5	95
PC3.2			



a ***b***

Figure 1. Testing of specimens with 100 mm length:
a — general view; *b* — basic scheme of the experimental setup:
1 — specimen under test; *2* — movable loading plate;
3 — fixed loading plate; *4* — indicator for registration of plates convergence

3. Results of the research

On the basis of the experimental results for each specimen, the diagrams of longitudinal deformation were generated in variables P — Δ, where P is the axial compressive load, Δ is the convergence between the pressing plates. For visual clarity and further analysis, the diagrams of pipe-concrete specimens (hereinafter referred to as $P_{pc}(\Delta)$) and hollow specimens (hereinafter referred to as $P_p(\Delta)$) with equal diameters were plotted in a common coordinate plane and with equal scale (Figure 2).

It can be seen from the diagrams (Figure 2) that the graphs of dependencies between axial load and longitudinal deformations have obvious similarity, being similar regardless of the pipe's diameter and thickness of wall. It can also be noted that the elastic stage of work both for steel pipe and for pipe-concrete ends at the same values of deformations, since the critical factor in the transition to the plastic stage is not the stress but the deformation of the steel pipe. The similarity of the graphs enables us to make an assumption that concrete in a pipe-concrete structure performs functions of strengthening a steel pipe, bringing a certain contribution to the load-bearing capacity of the cross-section at each stage of deformation.

The difference between the ordinates of the diagrams corresponding to the load on the pipe-concrete specimen at a particular value of axial displacement Δ and the load on the hollow steel pipe at the same displacement is taken as a value that quantitatively characterizes the contribution of concrete to the load-bearing capacity of the pipe-concrete cross-section at each stage of deformation:

$$P_c(\Delta) = P_{pc}(\Delta) - P_p(\Delta), \tag{1}$$

or the relative contribution of concrete in dimensionless units is:

$$\rho_c(\Delta) = \frac{P_{pc}(\Delta) - P_c(\Delta)}{P_p^{cr}} \tag{2}$$

The calculations of the above characteristics for specimens with 60 mm diameter are summarized in Table 2.

Table 2 shows that the value of the relative contribution of concrete $\rho_c(\Delta)$ at all the stages of deformation is near to 0.5, and its average value is 49.8%.

In this case, the critical (maximum) load value that can be withstood by a hollow steel pipe 60x2 mm of the same length is $P_p^{cr} = 142.5$ kN, and the load-bearing capacity of a concrete specimen with diameter 56 mm and length 100 mm (differentiated load-bearing capacity of the pipe-concrete specimen's core) obtained as a result of the experiment is $P_c^{cr} = 28.2$ kN, which corresponds to $P_c^{cr}/P_p^{cr} = 0{,}198.$ in dimensionless units.

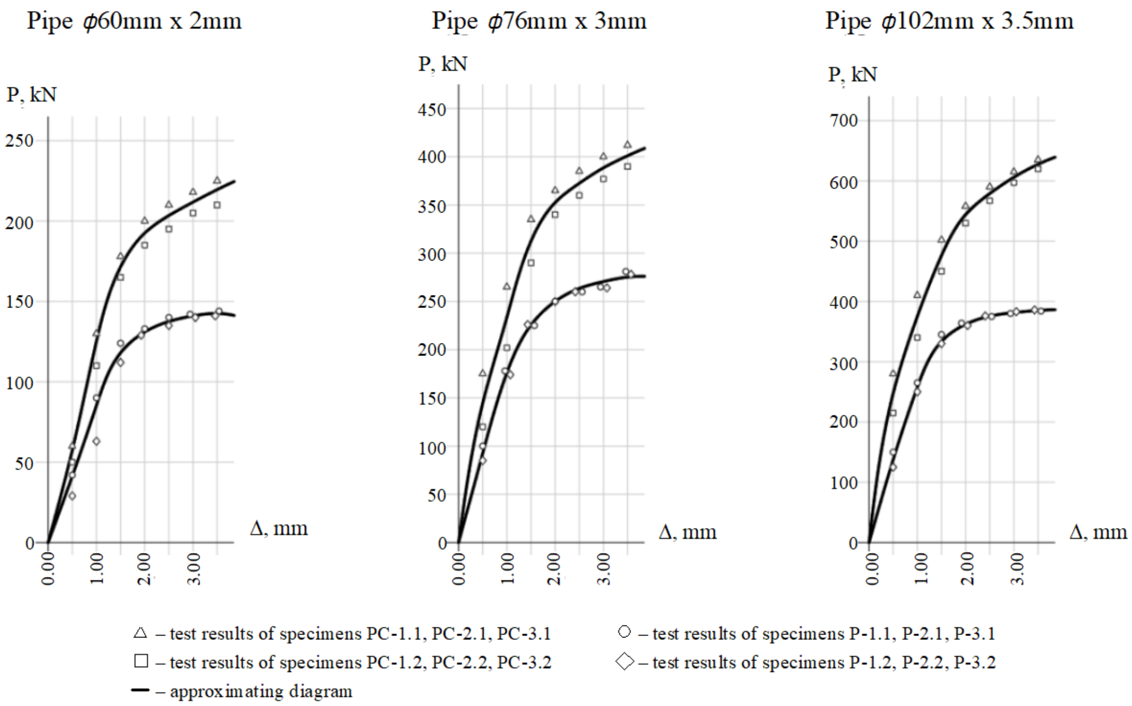


Figure 2. Diagrams *P*(Δ) based on the test results of specimens

Table 2

Calculation of concrete contribution for specimens made of steel pipes 60×2

Δ, mm	**Load *P*, kN**				$P_p(\Delta_i)$, **kN**	$P_{pc}(\Delta_i)$, **kN**	**Contribution of concrete**	
	P1.1	**P1.2**	**PC1.1**	**PC1.2**			$P_c(\Delta_i)$, **kN**	$\rho_c(\Delta_i)$
0.50	42	29	60	50	35.5	55	19.5	0.55
1.00	90	63	130	110	76.5	120	43.5	0.57
1.50	124	112	178	165	118	171.5	53.5	0.45
2.00	133	129	200	185	131	192.5	61.5	0.47
2.50	140	135	210	195	137.5	202.5	65	0.47
3.00	142	140	218	205	141	211.5	70.5	0.50
3.50	144	141	225	210	142.5	217.5	75	0.53

Similar calculations were performed on the test results of the remaining specimens made of 76×3 mm and 102×3.5 mm steel pipes. In this case, the average values of "concrete's contribution" were 41.0 and 50.9 %, with the relative bearing capacity of the concrete core P_c^{cr}/P_p^{cr} being equal to 0.158 and 0.210, respectively. Therefore, the contribution of concrete at each stage of deformation for all sizes of specimens is 2.5 times higher than the differentiated bearing capacity of the concrete core. This can be explained by the cladding effect, as the steel tube prevents the concrete core from deforming and breaking in the transverse direction due to Poisson's ratio [11; 16; 22]. As a result, the stress state of concrete transforms from longitudinal to triaxial compression, and its bearing capacity increases significantly. These effects, as well as the development of strength criteria for concrete under complex loading have been actively studied and presented in [23; 24].

Considering mentioned above, an experimental model of longitudinal deformation of the pipe-concrete specimen $P_{pc}(\Delta)$ was proposed according to the similar diagram for the steel pipe $P_p(\Delta)$:

$$P_{pc}(\Delta) = P_p(\Delta) \cdot \left(1 + 2.5 \cdot \frac{P_c^{cr}}{P_p^{cr}}\right), \tag{3}$$

where $P_{pc}(\Delta)$ and $P_p(\Delta)$ are the loads in the pipe-concrete element and steel pipe corresponding to the displacement Δ; P_p^{cr} and P_c^{cr} are destructive loads in the steel pipe and concrete core during their separate work, determined from tests under the axial compressive load of the corresponding specimens before destruction (differentiated bearing capacity).

The obtained model does not contradict to the generalized formula for determining the bearing capacity of pipe-concrete elements in [11], but at the same time it extends it, since it enables to describe the deformation process instead of only prognosing the moment of failure.

Figure 3 shows the diagrams for the pipe-concrete specimens obtained using formula (3) and their comparison with the experimental results.

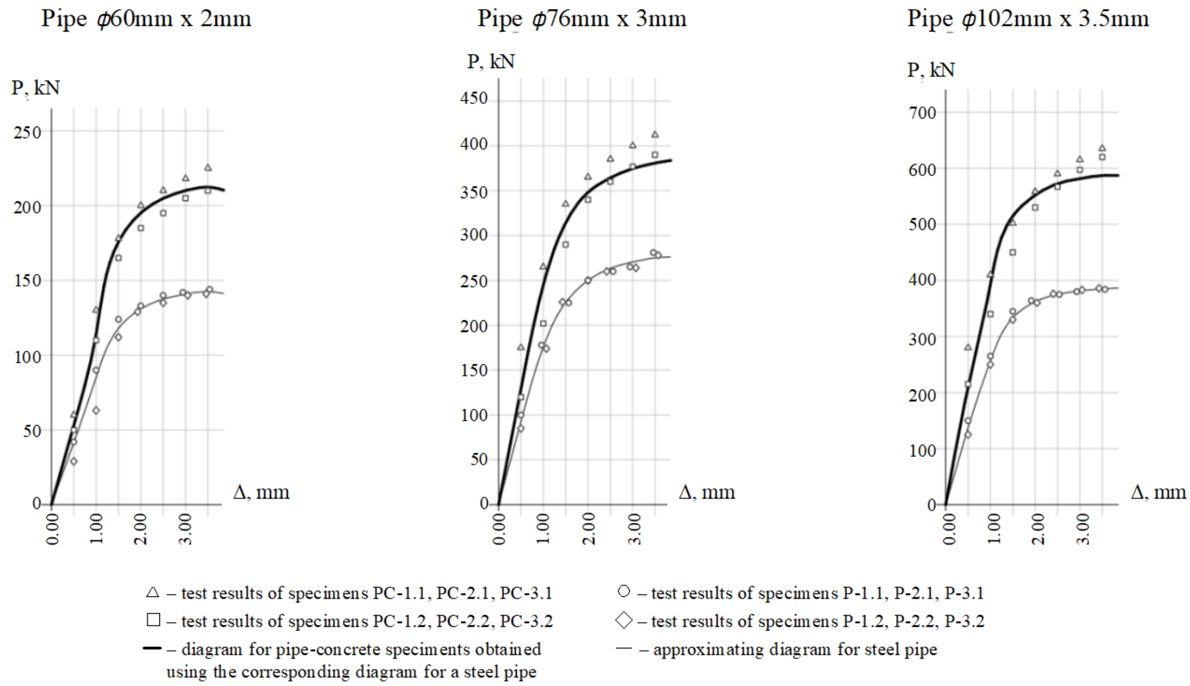


Figure 3. Diagrams $P(\Delta)$ for pipe-concrete specimens obtained using the corresponding diagrams for a steel pipe of the same diameter (according to formula 3)

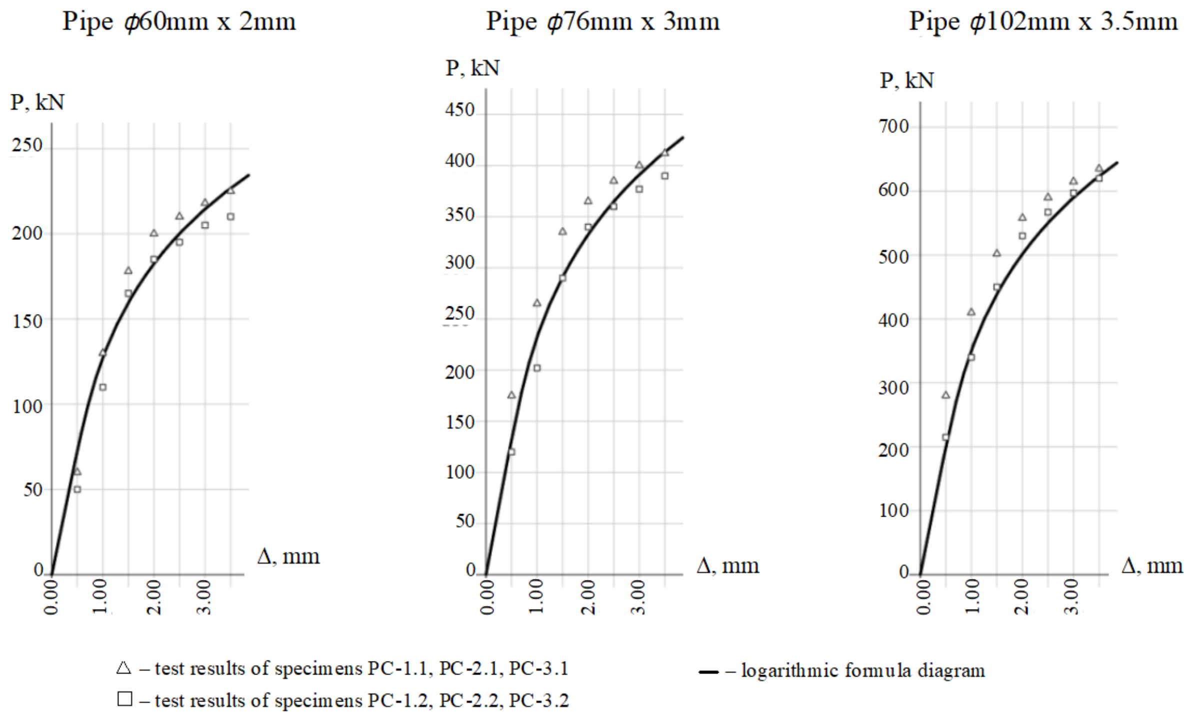


Figure 4. Diagrams $P(\Delta)$ for pipe-concrete specimens generated on the basis of the material mathematical model (according to formula 4)

Comparability of experimental data and the diagram (Figure 3) shows that the methodology of recalculation "via a steel pipe" can be used in engineering calculations. However, this approach is rather a graphical one and it is not suitable for using in mathematical modeling.

A mathematical model that analytically describes the longitudinal deformation of the pipe-concrete specimen was obtained based on the experimental data. The general view of the model is as follows:

$$P_{pc}(\Delta) = k_m \cdot P_p^{cr} \cdot \left(1 + k_c \cdot \frac{P_c^{cr}}{P_p^{cr}}\right) \cdot \lg(k_\Delta \cdot \Delta), \quad (4)$$

where the generalized coefficients are taken: $k_m = 0.85$ is the coefficient of model scaling; $k_c = 2.5$ is the coefficient of concrete contribution to the work of the structure; $k_\Delta = 500$ is the coefficient of scaling for displacements.

The coefficients k_m, k_c, k_Δ have been determined empirically, and their dependence on the physical and mechanical properties of the materials used and their proportions is obvious. Researches in this field are currently being carried out.

Figure 4 shows the diagrams generated in accordance with (4) and the experimental results.

4. Conclusion

The following conclusions can be made on the basis of the conducted research:

1. The contribution of concrete remains the same at any stage of deformation, that emphasizes the ability of concrete as part of a pipe-concrete element not to be excluded from work at loads exceeding the destructive load for a concrete specimen of the corresponding diameter, i.e., the ability to work over the limit of its differential bearing capacity. This can be explained by the occurrence of a triaxial stress state in the concrete due to the additional radial stresses caused by the shell. The steel shell prevents excessive transverse deformations leading to detachment of concrete fragments.
2. The deformation of the pipe-concrete element under central compression occurs in proportion to the deformation of the hollow steel element with the same diameter. In this case, the concrete plays a supporting role, preventing early loss of wall stability. The reduction of the specimen's load-bearing capacity occurs beyond the zone that is critical for the concrete, and the deformation coincides with the critical deformation for the hollow steel specimen.
3. The deformability of pipe-concrete elements under central compression can be described by a logarithmic dependence, allowing to form a mathematical model of the material. Despite the fact that the "smooth" analytical model (Figure 4) does not fully represent the nature of deformation of the specimens (Figure 2), its mathematical representation (4) can be used in describing the deformation processes of complex systems including steel-concrete structures with various combinations of pipe and concrete core cross sections. The proposed model does not consider the non-uniformity of stress distribution at the ending sections of the rods loaded with axial compressive load, but it can be applied for sections that are distant from the ending sections. For more accurate calculations and detailed representation of the stress-strain state of steel-tube-concrete rods, it is necessary to study in details and conduct tensometric tests on longer specimens, and this should be the following stage of research.

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