DOI:10.22337/2587-9618-2024-20-2-34-45

ELASTOPLASTIC DEFORMATION OF STEEL CONCRETE BEAMS WITH LOCAL BUCKLING UNDER THREE-POINT BENDING

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Abstract: In recent decades, there has been increased interest in studying the stress-strain state of concrete-filled steel tube constructions – composite elements consisting of a steel shell tube and a concrete core in a state of triaxial compression. In this combination, steel and concrete can achieve better strength and deformation characteristics than when they work separately, which makes it possible to design safe and economical structures. This article presents the results of an experimental study of the deformation process of bent concrete-filled steel tube elements of small circular sections. It is shown that with three-point transverse bending of a tubular concrete beam, in addition to deflection due to the curvature of the rod axis, deformations of local crumpling in places of application of concentrated loads have a significant effect on vertical displacement. The possibility of applying the classical theory of bending of a hollow steel beam according to the Bernoulli model is evaluated. The test results and deformation diagrams of hollow steel pipes (analytical and experimental data) and steel-reinforced concrete pipe beams filled with concrete are compared. A qualitative and quantitative assessment of the contribution of the presence of a concrete core to the bearing capacity and deformability (including local crumpling) of the element was carried out. The presence of a concrete core in a composite rod gives a significant weighting of the structure, however, in the case of off-center compression of the load-bearing vertical elements of multi-storey buildings, the effectiveness of using tubular concrete elements is very effective.

Keywords: pipe concrete, three-point bending, Bernoulli model, beam bending theory, elastoplastic deformation, triaxial compression of concrete, complex stress-strain state, efficiency of pipe concrete, load bearing capacity

УПРУГОПЛАСТИЧЕСКОЕ ДЕФОРМИРОВАНИЕ СТАЛЕБЕТОННЫХ БАЛОК С ЛОКАЛЬНЫМ СМЯТИЕМ ПРИ ТРЕХТОЧЕЧНОМ ИЗГИБЕ

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Аннотация: В последние десятилетия наблюдается повышенный интерес к изучению напряженно-деформированного состояния трубобетонных конструкций – композитных элементов, состоящих из стальной трубы-оболочки и бетонного сердечника, находящегося в состоянии трехосного сжатия. В таком сочетании сталь и бетон позволяют достичь лучших прочностных и деформативных характеристик, чем при их раздельной работе, что позволяет проектировать безопасные и экономичные конструкции. В настоящей статье приводятся результаты экспериментального исследования процесса деформирования изгибаемых трубобетонных элементов малогабаритных круглых сечений. Показано, что при трехточечном поперечном изгибе трубобетонной балки помимо прогиба за счет искривления оси стержня, существенное влияние на вертикальные перемещению оказывают деформации локального смятия в местах приложения сосредоточенных нагрузок. Проводится оценка возможности применения классической теории изгиба полой стальной балки по модели Бернулли. Сопоставляются результаты испытаний и диаграммы деформирования полых стальных труб (аналитические и экспериментальные данные) и сталежелезобетонных балок труб, заполненных бетоном. Произведена качественная и количественная оценка вклада наличия бетонного сердечника на несущую способность и деформативность (в т.ч. местное смятие) элемента. Наличие бетонного сердечника в композитном стержне дает существенное утяжеление конструкции, однако в случае внецентренного сжатия несущих вертикальных элементов многоэтажных зданий эффективность применения трубобетонных элементов весьма эффективно.

Ключевые слова: трубобетон, трехточечный изгиб, модель Бернулли, теория изгиба балок, упругопластическое деформирование, трехосное сжатие бетона, сложное напряженно-деформированное состояние, эффективность трубобетона, несущая способность

1. INTRODUCTION

In recent decades, steel-concrete rods have attracted increased interest from domestic [1-10] and foreign scientists [11-23], since they allow the most complete combination of the main advantages inherent in both metals and concrete, while leveling or completely eliminating their disadvantages [2, 3, 10]. Thus, steel structures are very strong, but, due to their good elastic properties, they practically don’t damp mechanical energy. It makes their use in conditions of oscillations and vibrations difficult and requires the appliance of special vibration and seismic protection systems [11]. In turn, reinforced concrete elements with a commensurate load-bearing capacity are much more massive and have poor resistance to the accumulation of damage and the initiation and development of cracks. The use of steel-concrete elements formed by enclosing reinforced concrete or concrete in a steel cage also leads to a nonlinear increase in load-bearing capacity due to the transition of the core to a triaxial stress state [1, 4-10, 24-27].

At present, many experimental and numerical studies have been carried out to study the strength and stability of pipe concrete structures (PCS) under central and eccentric compression [1-3, 5-7, 9, 10]. However, the bending work of such rods remains poorly studied. The main reason for this is the irrationality of using PCS as a load-bearing bending element (pipe-concrete beam - hereinafter referred to as PCB) due to the small increase in load-bearing capacity with significant weight. At the same time, in real operating conditions [8], it is almost impossible to identify a purely compressed element, and to analyze compressed-bent elements, a detailed study of the work under pure and transverse bending of rods of various flexibility is necessary. Of particular interest is the bending of massive PCB, the characteristic cross-sectional size of which is about 10% of the length, since in such elements it is not always possible to apply the classical models of Bernoulli or Timoshenko beams. This is primarily due to the fact that the distribution of internal forces into elementary components (moment and shear force) becomes difficult, and the transition from forces to stresses is complicated by the “composite” nature and internal static indetermination of the steel-concrete section [1-3].

Under conditions of three-point bending, significant local stresses arise in the PCB, leading, in addition to general curvature, to local deformation at the force points (Fig. 1). Conducting experimental studies in this case is the most rational for assessing the general stress-strain state of a massive PCB during bending with local compression.

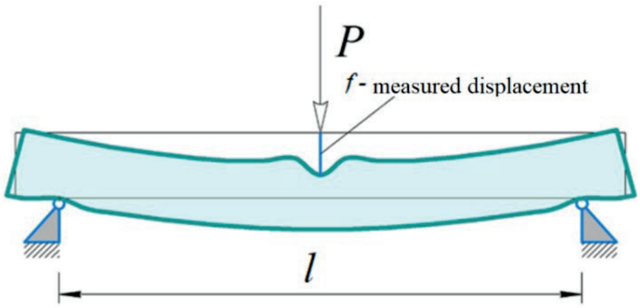

Figure 1. Deformation of the PCS under three-point bending

The research [31] considers the bending of PCB using Bernoulli beam theory, as a result of which the equivalent bending stiffness is determined. The main disadvantage of the study is the idealization and assumptions of work with a predominance of normal stresses (bending model of a Bernoulli beam), which is a very rough approximation due to the factors indicated above.

2. MATERIALS AND RESEARCH METHODS

To analyze the stress-strain state, experimental and numerical simulations were carried out under three-point bending. To conduct experiments, PCB samples with a length of 700 mm were made using steel pipes with a cross section of Ø76x3, Ø102x3.5 mm, steel grade 09G2S. To create the core, fine-grained concrete of class B12.5 was used. To confirm the grades and characteristics of the PCB components, compression tests were carried out on control samples [2, 3].

Fig. 2 shows the experimental setup. In the experiment, a span of 600 mm was assumed, i.e. the ratio of the span to the transverse size of the sample was l/D = 1/7.89; 1/5.88.

During testing, a smooth load was applied to sample 1 using a load crossbeam 2. Using indicator 4, the general approach of the traverses was recorded, that is, the curvature of the sample as a result of pure bending of the bend and local crushing.

To assess the contribution of the concrete core to the deformation of PCS, control samples of hollow pipes with a length of 700 mm and a cross section of Ø76x3, Ø102x3.5 mm (steel grade 09G2S) were additionally manufactured. The need for this part of the study is dictated by the fact that, based on the Bernoulli model, a hollow pipe has fairly good performance in transverse bending due to the high values of the moments of inertia of the undeformed section. However, studies on the performance of flexural thin-walled structures have shown that local deformation, cross-sectional bending and metal collapse are fundamental in structures of this type and significantly reduce the overall stiffness and load-bearing capacity [32]. Fig. 3 shows a basic view of the deformed state of a thin-walled beam and the difference between the Bernoulli model and the real structure.

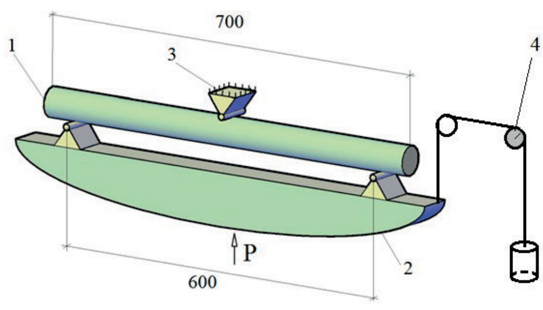

Figure 2. Experimental setup for testing PCS for three-point bending: 1 – sample under study, 2 – movable cargo cross-beam, 3 – static cross-beam, 4 – dial-type movement indicator

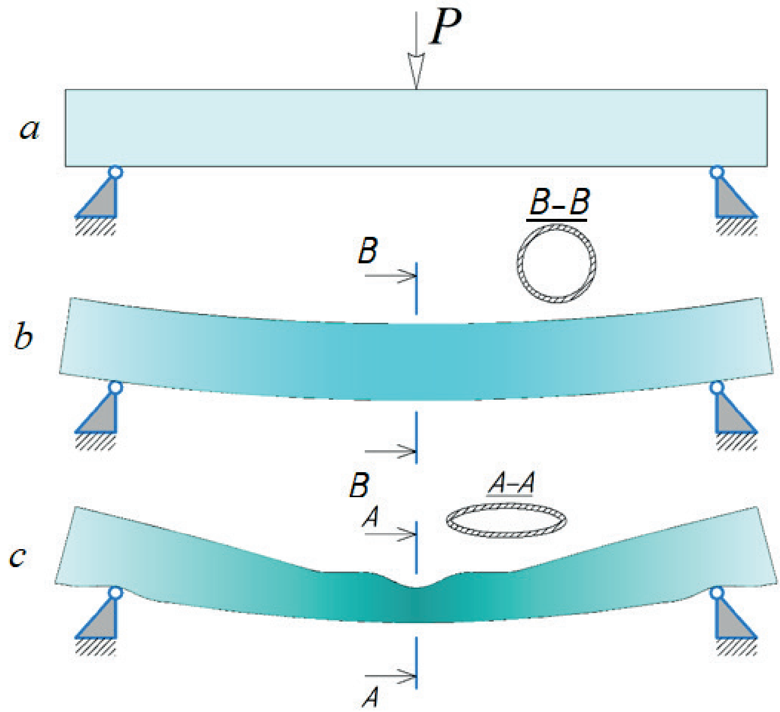

Figure 3. Calculation diagram of the bending element (a), diagram of deformations according to the Bernoulli model (b) and taking into account the curvature of sections and local crushing (c)

3. RESULTS OF THE EXPERIMENTAL RESEARCH

During the research, samples of PCB and hollow pipes were brought to destruction or complete loss of load-bearing capacity. In this case, the measured deformations were obviously not divided into "bending" and "bearing deformations", since in this study the interest is precisely the general stress-strain state of the sample with local collapse during three-point bending. Fig. 4 shows a typical type of PCB failure during three-point bending.

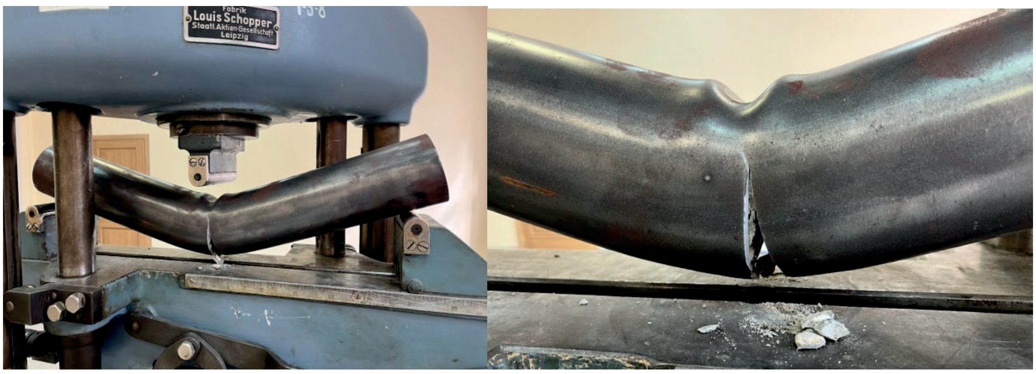

Figure 4. Destruction of PCB along the normal section

Fig. 5 shows diagrams of elastoplastic deformation of PCB samples, showing the dependence of the load on the sample and the approach of the traverses $P(f)$, (Fig. 1). The diagrams show that at the initial stage the work of the samples is close to elastic, and the transition to a nonlinear dependence occurs at the same displacements $f \approx 6$ mm.

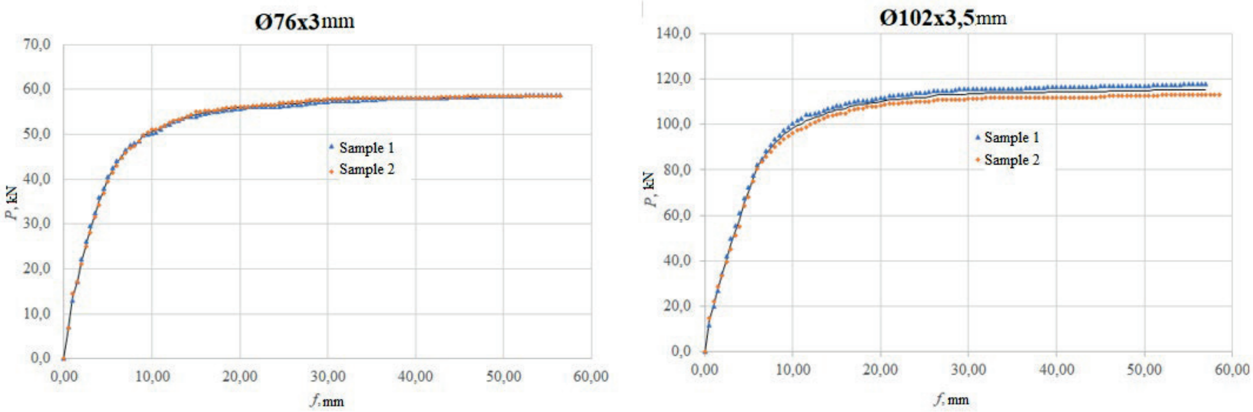

Figure 5. Deformation diagrams of PCB samples

As expected, despite the destruction along the normal section (Fig. 4), there are significant local deformations in the beam due to the collapse of the steel pipe. Nevertheless, the deformations did not lead to a global change in the shape and dimensions of the PCB cross sections. Moreover, in almost the entire linear section of the diagram (Fig. 5), bending deformations prevailed over crushing (Fig. 6).

Figure 6. Appearance of the sample under linear deformation

In Fig. 7 compares the deformation of the PCB in a linear section with the deformation of an equivalent hollow pipe according to the Bernoulli beam model (Fig. 3b), according to which, in the absence of local deformations, the diagram is described by the dependence:

$$f = \frac{Pl^3}{48EJ}, \qquad (1)$$

where: f, P, l – measured displacement, load, beam span (Fig. 1); $E = 2{,}06 \cdot 10^5$ MPa – Young's modulus of pipe material; $J = \pi(D-d)^4/64$ – axial moment of inertia of the pipe section (D, d – outer and inner diameters), and the bearing capacity can be determined from the Navier condition:

$$\frac{M}{J} \cdot \frac{D}{2} \le R_c, \qquad (2)$$

where: $M = Pl/4$ – maximum bending moment in beam sections; $R_c =$ 320 MPa – calculated resistance to the yield strength of steel grade 09G2S.

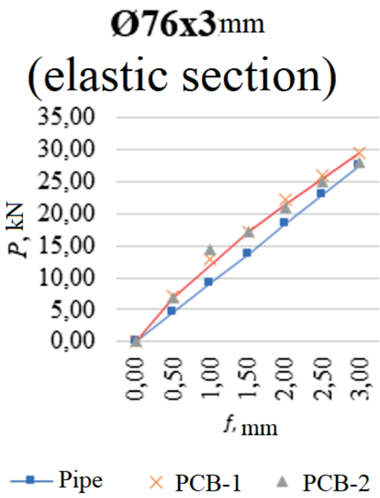

Figure 7. Diagrams of linear deformation of a hollow pipe (according to the Bernoulli model) and pipe-concrete samples

The diagrams show that, compared to the Bernoulli bending deformation model, the presence of a concrete core in the pipe leads to strengthening of the structure. It should be taken into account that the actual operation of a thin-walled pipe under three-point bending is noticeably different from the Bernoulli beam model. Fig. 8 shows experimental deformation diagrams and the appearance of hollow pipe samples after testing. Real data obtained experimentally (Fig. 8) indicate that the load-bearing capacity of a hollow pipe is significantly lower than the calculated values according to (2). Table 1 provides a comparative analysis of the load-bearing capacity of PCB and hollow pipes according to the Bernoulli model and according to experimental data (after the load-bearing capacity value, the percentage relative to the Bernoulli model is given). According to the data given in Table 1, it is clear that an increase in diameter critically affects the load-bearing capacity of a hollow sample, which is explained by an increase in the flexibility of its cross-section and a sharp increase in the influence of bearing deformations.

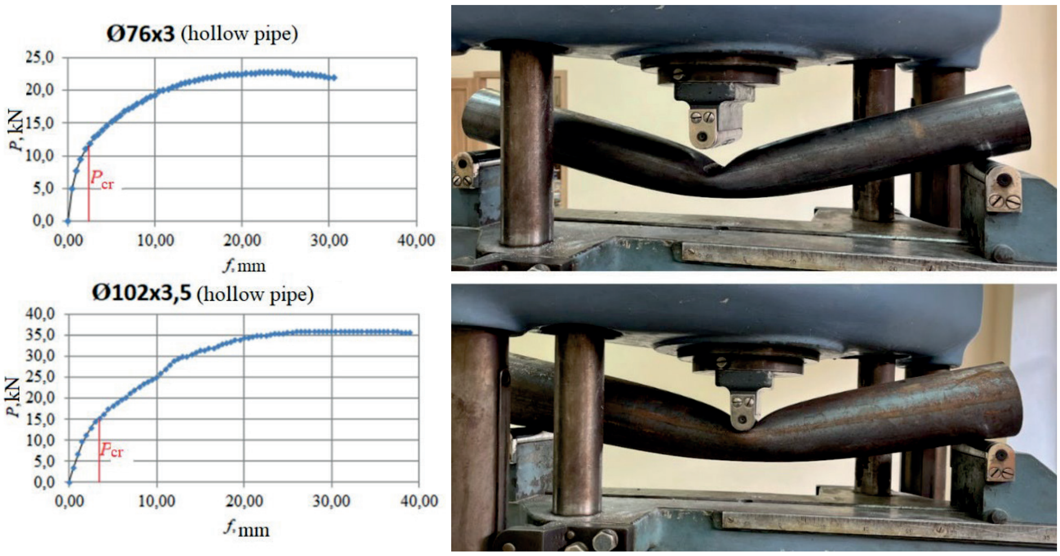

Figure 8. Deformation diagrams and view of hollow pipe samples after testing

Table 1. Comparison of the load-bearing capacity of hollow and pipe concrete beams

Sample size	Load-bearing capacity, kN		
	PCB (Fig.5)	Hollow pipe	
		Bernoulli model (formula 2)	Experiment (Fig. 8)
Ø76x3	44 (169%)	26 (100%)	12 (46%)
Ø102x3.5	87 (158%)	55 (100%)	15 (27 %)

Fig. 9 shows a comparison of the actual strain diagrams of a PCB and a hollow pipe under three-point bending. As can be seen from the diagrams, the presence of a core in a thin-walled bending pipe significantly improves its strength and deformation characteristics. It should also be noted that despite the plastic properties of concrete enclosed in a core, the deformation of PCB by its nature is more reminiscent of the behavior of metals (for example, with an obvious plastic zone in the graphs (Fig. 9). At the same time, a hollow pipe due to crushing and curvature cross sections immediately deform nonlinearly, which complicates the calculations when designing such structures.

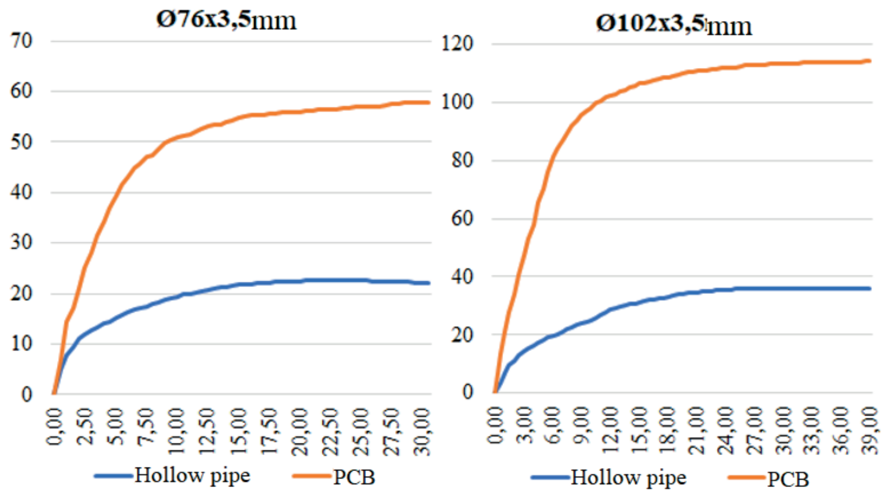

Figure 9. Experimental diagrams of deformation of PCB and hollow pip

4. CONCLUSIONS

Based on the results of the experimental research, it was established that the presence of a concrete core primarily ensures the resistance of the metal pipe to crushing and local deformation of the section. The contribution of the concrete core to the load-bearing capacity for the two diameters was about 60% compared to the Bernoulli model, and compared to the experimentally tested hollow pipe, the load-bearing capacity increased by about 3 times. Despite the significant weight, the use of bendable pipe-concrete structures may be advisable if, along with bending, compressive forces occur in the sections (for example, columns of multi-story buildings), since the concrete core significantly strengthens structures of this kind [1-3].

The use of classical models of beam bending in the case of thin-walled pipe structures is irrational and provides unnecessary margins, since it does not take into account local collapse and deformation of sections. The design of massive bendable PCB should be carried out taking into account local deformations.

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