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BEARING CAPACITY OF T-BEAMS WITH A FLANGE MADE OF HIGH-STRENGTH CONCRETE AND LONGITUDINAL REINFORCEMENT OF CLASS A500C

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Abstract: Experimental and numerical studies of the bearing capacity and deformation of T-beams with a flange made of high-strength concrete and longitudinal reinforcement of class A500C with a web made of concrete of ordinary strength were carried out on prototypes of beams and numerical models. The beams being tested are considered at different percentages of reinforcement. The calculation scheme of the beams corresponded to a four-point bend.

As a result of experimental and numerical studies, the nature of the destruction of beams, their deformation and the nature of cracking are determined. Experimental and numerical relationships of relative deflections on relative bending moments are obtained. A comparative analysis of the values of the bearing capacity and the relative height of the compressed zone of the beams, obtained experimentally, numerically and according to SP 63.13330.2018, was carried out. The nature of the distribution of deformations in concrete of normal section of beams at different levels of loading is determined.

Keywords: T-beam, flange made of high-strength concrete, longitudinal reinforcement of class A500C, load-bearing capacity, deformation

НЕСУЩАЯ СПОСОБНОСТЬ БАЛОК ТАВРОВОГО ПРОФИЛЯ С ПОЛКОЙ ИЗ ВЫСОКОПРОЧНОГО БЕТОНА И ПРОДОЛЬНОЙ АРМАТУРОЙ КЛАССА А500С

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Аннотация: Экспериментальные и численные исследования несущей способности и деформативности балок таврового профиля с полкой из высокопрочного бетона и продольной арматурой класса А500С с ребром из бетона обычной прочности проведены на опытных образцах балок и численных моделях. Исследуемые балки рассмотрены при различных процентах армирования Расчетная схема балок соответствовала четырехточечному изгибу.

В результате проведения экспериментальных и численных исследований определен характер разрушения балок, их деформации и характер трещинообразования. Получены экспериментальные и численные зависимости относительных прогибов от относительных изгибающих моментов. Проведен сравнительный анализ значений несущей способности и относительной высоты сжатой зоны балок, полученных экспериментально, численно и по СП 63.13330.2018. Выявлен характер распределения деформаций в бетоне нормального сечения балок при различных уровнях нагружения

Ключевые слова: тавровая балка, полка из высокопрочного бетона, продольное армирование класса А500С, несущая способность, деформативность

INTRODUCTION

High-strength concrete is an efficient material with exceptional mechanical properties. The use of high-strength concrete makes it possible to obtain high values of bearing capacity and stiffness for beams [1–6]. However, high-strength concrete in the tension zone does not affect the bearing capacity. Therefore, in order to reduce material consumption and increase the efficiency of using the mechanical properties of construction materials, high-strength concrete should be used in the compressed zone of the beam, and in the tension zone, concrete of a class that would ensure compatibility with longitudinal reinforcement.

Studies of rectangular cross-section beams with high-strength concrete in the compressed zone have proven their effectiveness.[7–9] However, there are no studies of similar T-beams. In view of the fact that the T- cross section is less material-intensive and most used in split single-span reinforced concrete structures, it is a promising task to study reinforced concrete T- beams with a flange of high-strength concrete.

MODELS AND METHODS

Experimental studies were carried out on single-span beams. The size of the web is 60 x 100 mm, the flange are 240 x 20 mm, the span is 1200 mm, the total length of the beam is 1400 mm, the boundary of the two layers runs along the border of the flange and the web, respectively, the height of the upper layer of high-strength concrete is 20 mm. Steel rebar of class B500 with a diameter of 6 mm was used as transverse reinforcement. The transverse rebar enters the flange by 10 mm, thus performing the function of dowel bars and ensuring the joint operation of the two layers. To combine the reinforcement into a flat frame, mounting steel rebar of class B500 with a diameter of 6 mm was used. The studies were carried out on beams with a percentage of longitudinal reinforcement of 0.7–3.5%. Class of longitudinal rebar is A500C. In order to ensure the joint operation of the longitudinal rebar and the web, anchor devices in the form of steel angles were welded to the longitudinal rebar. The design and calculation scheme of the beam are shown in fig. 1

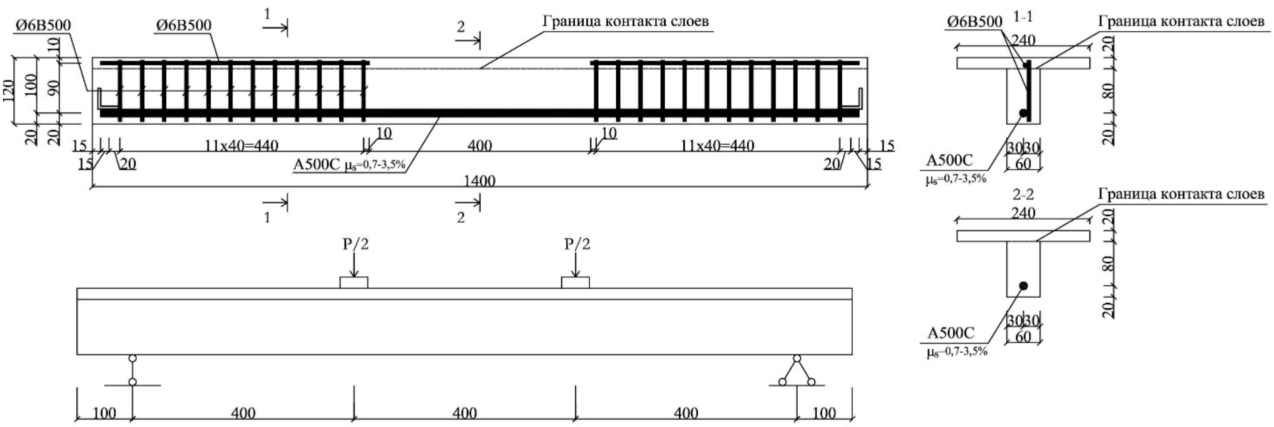

Figure 1 – Design and calculation scheme of beams

The control of the main mechanical characteristics of concrete and rebar was carried out by testing control samples of concrete prisms with a size of 70x70x280mm, in accordance with STST 24452-80 "Methods for determining prism strength, modulus of elasticity and Poisson's ratio", and reinforcing bars in accordance with STST 12004-81 "Reinforcing steel. Tensile test methods. The test results are shown in table 1, 2.

Table 1. Basic parameters of beams

Beam code	Working section height h_0, mm	Longitudinal reinforcement diameter d_s, mm	Percentage of longitudinal reinforcement μ_s	Compressive strength of high-strength concrete $R_{1b,n}$, MPa	Compressive strength of concrete of second layer, $R_{2b,n}$, MPa
DTB -1	100	8	0,70%	94,64	22,3
DTB -2	95	10	1,10%	94,64	22,3
DTB -3	99	12	1,60%	82,5	23,25
DTB -4	92	14	2,10%	82,5	23,25
DTB -5	102	16	2,80%	88,48	41,07
DTB -6	97	18	3,50%	86,3	41,07

The beams were tested on an INSTRON 600 kN hydraulic press (fig. 2). To determine the stress-strain state of the beams, the relative deformations of the normal section were recorded. The correlation of the load level, values of relative deformations and deflections is provided by the multi-channel measuring system MGCplus. The layout of strain gauges and deflection meter is shown in figure 2.

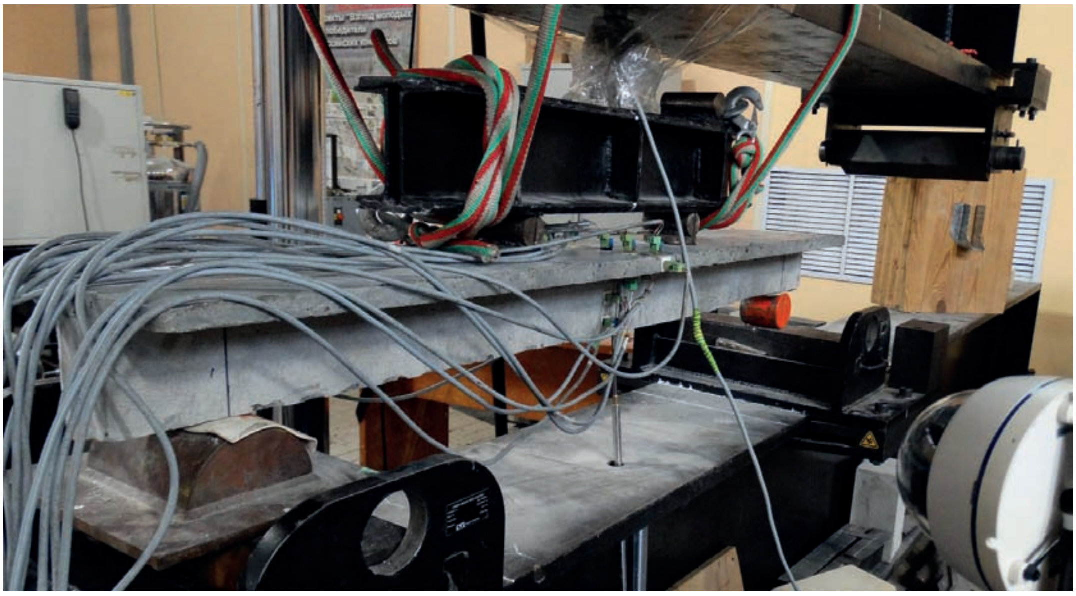

Figure 2 –General view of experiments on the beams

Table 2. Mechanical characteristics of A500C rebar

Rebar diameter, mm	Yield strength σ_y, MPa	Elastic modulus E_s, MPa	Deformation at yield strength ε_{s0}, %	Deformation corresponding to the end of the yield platform ε_{s2}, %
8	758,9	220921	0,34	2,5
10	610,9	206510	0,31	2,5
12	580,5	205470	0,32	2,5
14	551,2	210160	0,28	2,5
16	618,4	197210	0,3	2,5
18	580,6	213200	0,31	2,5

Finite element analysis (FEA) of beams, taking into account the nonlinear properties of materials, was performed using the «ANSYS 2022 R2» software package (fig. 3). Eight-node finite elements (FE) of the Solid 65 type were chosen for the finite elements of the concrete body. In this type of FE, the Willam-Warnke concrete strength criterion is implemented.[10] Reinforcing frame modeled with Beam 188 linear finite elements.

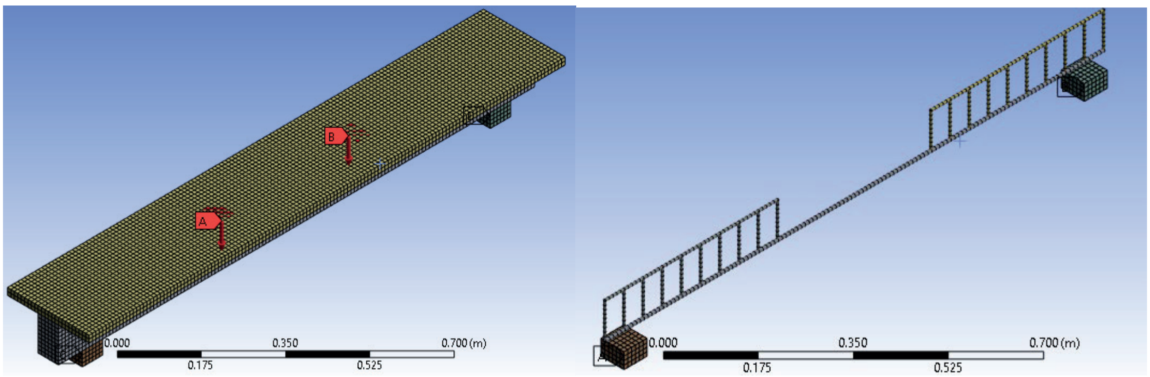

Figure 3 – General view of the numerical model

Table 3. Analysis of test results and numerical simulation of beams

Beam code	Ultimate bending moment, kN·m		Relative deflection		Relative height of compressed zone			Limiting relative height of the compressed zone, ξ_R
	$M_{ult,EXP}$	$M_{ult,ANSYS}$	$f_{ult,EXP}/l_0$	$f_{ult,ANSYS}/l_0$	X_{EXP}/h_0	x_{ANSYS}/h_0	X_{SP}/h_0	
DTB-1	2,71	3,48	1/154	1/146	0,13	0,18	0,02	0,23
DTB -2	4,42	4,56	1/166	1/184	0,13	0,18	0,02	0,26
DTB -3	6,44	6,26	1/169	1/191	0,2	0,196	0,03	0,26
DTB -4	7,88	7,98	1/152	1/165	0,26	0,199	0,05	0,28
DTB -5	11,85	12,12	1/149	1/141	0,18	0,2	0,06	0,25
DTB -6	13,91	13,92	1/133	1/141	0,15	0,2	0,08	0,27

RESEARCH RESULTS AND THEIR ANALYSIS

The destruction of all beams occurred after the occurrence of stresses in the rebar corresponding to the yield strength. The relative deflection, at the time of failure, significantly exceeded the maximum allowable - 1/123 of the span (SP 20.133330.2016 "Loads and Impacts") and was in the range of 1/15–1/55 of the span. A large scatter of values is associated with different types of destruction. In the beam DTB-1, the destruction is caused by the achievement of stress reinforcement equal to the limit of tensile strength. DTB-2 and DTB-3 were destroyed with crushing of concrete in the compressed zone above the web. The destruction of DTB-4 - DTB-6 was local in nature and was caused by a split of the flange overhang.

Beam tests were accompanied by the development of normal and oblique cracks. The development of normal cracks took place along the height of the web with the transition to the lower part of the flange overhang and exit to the end part of the flange overhang. Horizontal shear cracks between the layers before the occurrence of stresses in the rebar corresponding to the normative tensile resistance were not determined. In beams DTB-4 - DTB-6 at the later stages of testing, the transformation of inclined cracks into horizontal ones was observed at the point of contact of the two layers. Also in these beams, horizontal cracks were found on the surface at the place of the future split of the flange overhang.

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The discrepancy between the experimental and numerical values of the bearing capacity is 1.27% - 28.6%. The greatest discrepancy between the results was found in the beam with the percentage of reinforcement μs=0.7% and corresponded to 28.6%. In the rest of the beams, the discrepancy between the values of the bearing capacity was in the range of 1.27%–3.08%. The values of the relative height of the compressed zone according to SP 63.13330.2018 «Concrete and reinforced concrete structures» are in the range of 0.02–0.08. The values of the relative height of the compressed zone were experimentally established in the range of 0.13-0.26 and did not exceed the values of the boundary height of the compressed zone according to SP 63.13330.2018 for each individual beam. The numerical values of the relative height of the compressed zone have a smaller divergence from the experimental ones and are in the range of 0.18–0.2.

An analysis of the relationships between relative deflection and relative bending moment (fig.6-8) allows us to determine two levels of stabilization of deflection values - during cracking and when the bearing capacity is exhausted. In finite element analysis (FEA), the relationship between stresses and relative strains in rebar and concrete is determined by a double-line strain diagram. The main parametric points of the diagrams are determined in accordance with SP 63.13330.2018 «Concrete and reinforced concrete structures» according to the test results of control samples. Deformation at yield strength of reinforcement is determined by expression (1) SP 63.13330.2018 «Concrete and reinforced concrete structures»:

$$\varepsilon_0 = \sigma_y / E_s \tag{1}$$

where, ε_0 – relative deformation corresponding to the yield strength of reinforcement; σ_y – stress corresponding to the yield strength of reinforcement; E_s – elastic modulus of rebar.

In connection with the use of a double-line diagram of steel rebar deformation in the numerical model, the divergence of deflection values at M_{ult} was 5%–13.04%. It is possible to improve the convergence of results by using more complex charts.

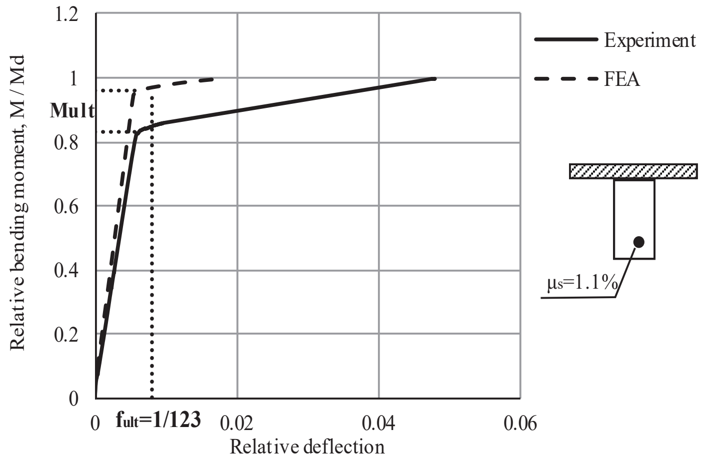

Figure 4. Relationship between relative deflection and relative bending moment for a beam with reinforcement percentage μ=1,1%

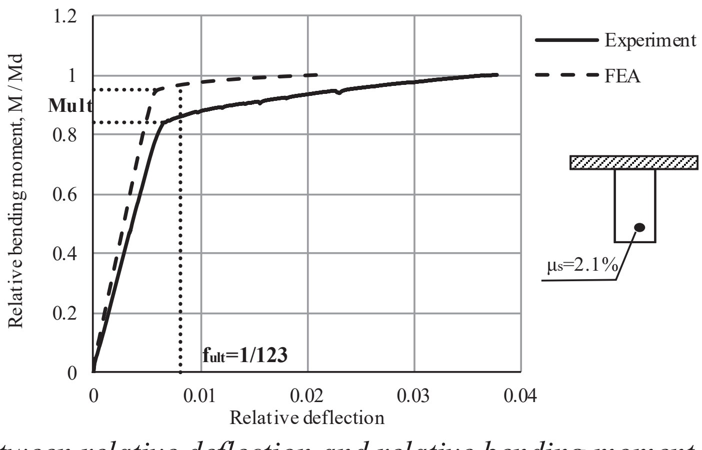

Figure 5. Relationship between relative deflection and relative bending moment for a beam with reinforcement percentage μ=2,1%

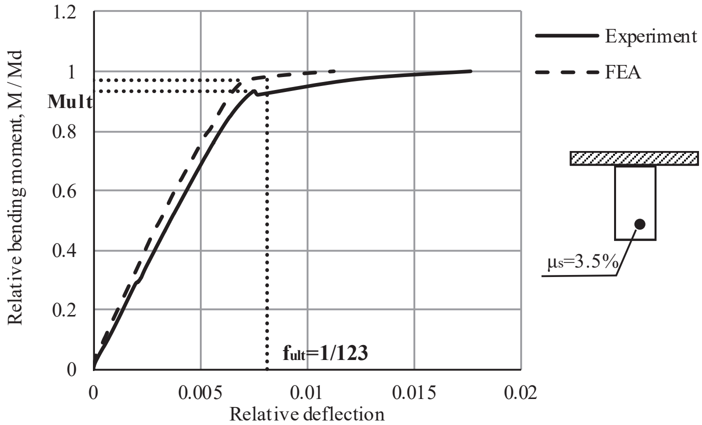

Figure 6. Relationship between relative deflection and relative bending moment for a beam with reinforcement percentage μ=3,5%

The limiting relative strain of a double-line diagram of rebar deformation - ε_2 has a value of $25 \cdot 10^{-3}$, and the stress, at a given point in the diagram, corresponds to the yield strength of the rebar. In this connection, the numerical values of the breaking moment and the corresponding deflection of the beam are lower than the experimental values. Graphs (fig. 4-6) make it possible to make sure that with an increase in the percentage of reinforcement, the relative deflection corresponding to the breaking moment decreases.

The nature of concrete deformations in samples with a reinforcement percentage of 0.7% and 1.1% at the border of adjacent layers there are gaps in the nature of the development of relative deformations (fig. 7). A similar nature of deformations corresponds to the development of deformations in composite structures [11–15]. The nature of the development of concrete deformations along the height of the section, obtained by calculating the FEM at M_{crc}, has a linear form due to the conjugation of two layers by rigid nodes. At the stage of loading M_{ult}, the lower layer is subject to cracking, and the nature of deformations in the compressed zone of normal section has a linear form (fig. 8). The nature of the development of deformations at M_{ult}, obtained by the calculation of the FEM, contains a deviation from the linear law.

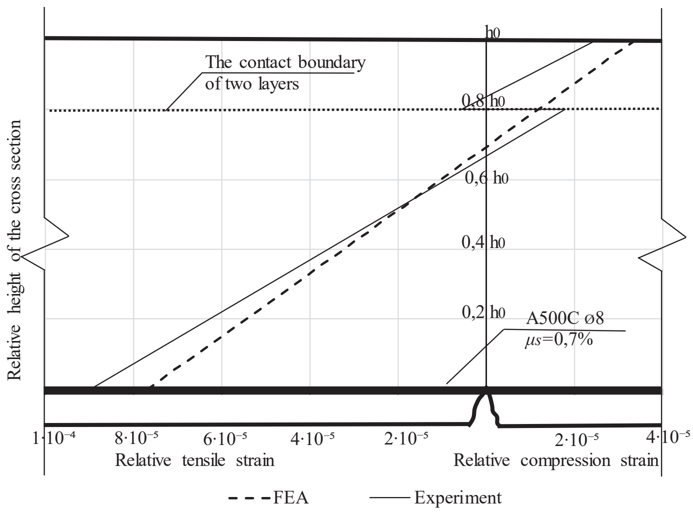

Figure 7. The nature of deformations in concrete of normal section of a beam with a percentage of reinforcement μ=0,7% at Mcrc

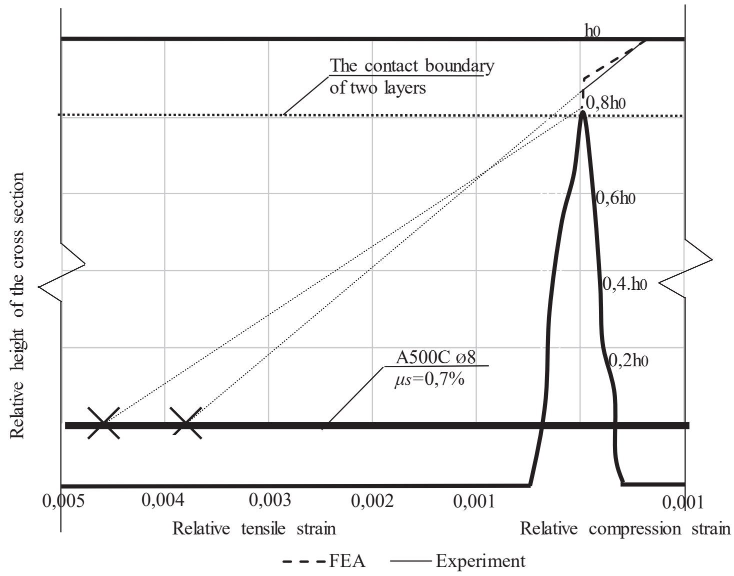

Figure 8. The nature of deformations in concrete of normal section of a beam with a percentage of reinforcement μ=0,7% at Mult

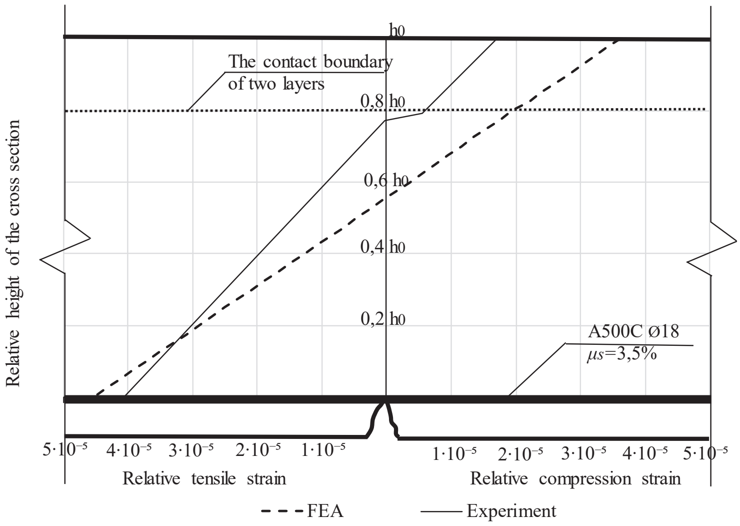

Figure 9. The nature of deformations in concrete of normal section of a beam with a percentage of reinforcement μ=3,5% at Mcrc

In samples with a reinforcement percentage of 1.6%–3.5%, the gap in the values of relative deformations of concrete was qualitatively different and can be caused by the presence of different-modulus materials of adjacent layers in the boundary of the compressed zone of the normal section of the beam [11]. With a bending moment equal to M_{ult}, the boundary of the compressed zone did not go beyond the contact surface of the two layers, and the diagram had a linear form. The distribution of concrete deformations, obtained in the calculation of the FEM, at M_{crc} had a linear form (fig. 9). At M_{ult} , according to the FEM calculation, the compressed zone included the outermost fibers of the second layer, in connection with which a pattern with a rupture of deformations was obtained, which is caused by the presence of different-modulus materials of adjacent layers in the boundary of the compressed zone of the normal section of the beam (fig. 10).

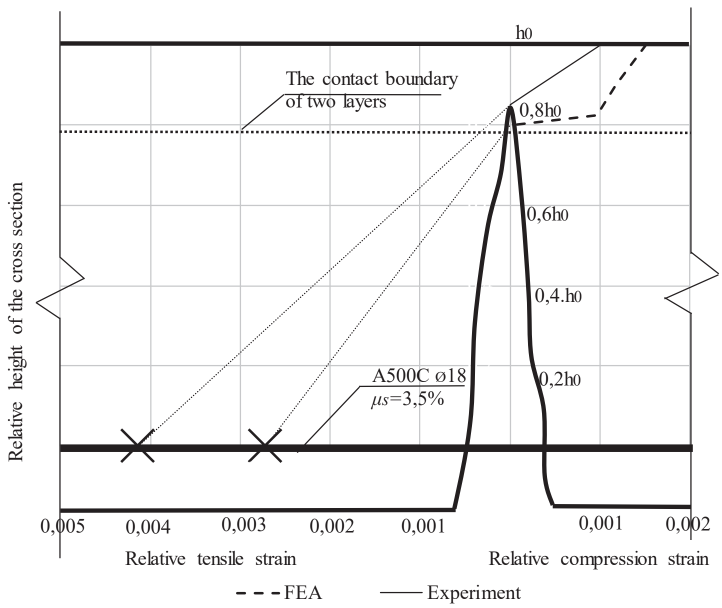

Figure 10. The nature of deformations in concrete of normal section of a beam with a percentage of reinforcement μ=3,5% at Mult

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CONCLUSIONS

As a result of experimental and numerical studies of the bearing capacity and deformation of beams, it has been established that the method for determining the relative height of the compressed zone according to SP 63.13330.2018 «Concrete and reinforced concrete structures» requires clarification in the case of calculating T-beams with a flange of high-strength concrete and longitudinal reinforcement A500C. It was also found that the numerical values of the bearing capacity have acceptable convergence not for all percentages of reinforcement, and the nature of the distribution of deformations in concrete does not correspond to the experimental data. In this connection, it is necessary to develop a method for calculating T-beams with high-strength concrete in the flange and longitudinal reinforcement A500C, which would allow with the necessary accuracy to determine the relative height of the compressed zone and the bearing capacity of the beams at various percentages of reinforcement, as well as to determine a reliable picture of the nature of deformations in concrete beams by section height.

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