Reinforcing clamps: stress-strain state of bent reinforcement

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Abstract. The aim of the work is to study the stress-strain state of reinforcing bars during bending and to obtain the appropriate formulas and dependencies to clarify the possible boundaries of the use of mandrels for reinforcement of various classes and diameters. The object of the study are bending bars used as transverse reinforcement in the design of linear reinforced concrete elements. The study determines the possible limits of use for various classes of bars, where the relative deformations of steel do not go beyond the yield strength. A formula is obtained for calculating the possible limiting diameters of mandrels D for various diameters of bent bars d. The limiting diameter of the mandrel depends only on the relative standard elongation of the extreme fiber of the bent bar Graphs of relative elongations of the extreme fiber of the bars are plotted for different diameters of a bent bar made of reinforcement of classes A240, A400, A500S. The calculated values of relative elongations in percent are calculated for plain bars and ribbed bars with diameters from 6 to 28 mm.

Keywords: reinforced concrete, bend, curvature, mandrel, relative deformation, transverse reinforcement, collar.

1 Introduction

In the Russian Federation, Europe, the USA and other countries, the limit state design method is used in the design of reinforced concrete elements. This method is guaranteed to provide strength, durability, survivability and safety of structures during the entire period of exploitation. The practical implementation of the method is presented in various regulations: in the Russian Federation it is SP 63.13330.2018 "Concrete and reinforced concrete structures. General Provisions"; in Europe - "Eurocode 2", in the USA - ACI 318-05 and so on.

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Regulations pay attention to the strength and safety of structures in the first place. Additional costs for the manufacture of elements, transportation and installation are paid less attention. Economics in the design of reinforced concrete structures is usually aimed at minimizing the direct costs of materials: concrete, reinforcement, formwork, and so on. The issues of optimal design of structures are practically not considered in the regulations.

The problem of optimal design of reinforced concrete elements was considered in the works of Russian and foreign scientists. In Russia, Skladnev N.N., Sushkova S.N., Tuychiev N.D. and others dealt with the topic of optimal design of reinforced concrete structures, taking into account reliability and efficiency.

Tamrazyan A.G. and Aleksejtsev A.V. were engaged in the optimization of structures, taking into account the ratio of production costs and the risks of material losses in emergency situations. [1]. Chakrabarti B.K. studied the relationship between the cost of the beam, the unit cost of materials and the dimensions of the beam [2]. Coelho C.K., Santos F.E. and Alonso F.F. used genetic algorithms for the optimal design of beams [3]. Garsteki A., Glema A. and Sigallo J. developed a software package for the optimal design of reinforced concrete beams and columns [4]. Dembi M. dealt with the problem of optimal and safe design of reinforced concrete elements [5]. Kuznetsov V.S. and Shaposhnikov Yu.A. studied the issues of establishing the optimal parameters of a reinforced concrete rectangular beam, and also dealt with the problems of reducing the consumption of transverse reinforcement in beams [6, 7, 8]. Jensen S., Minelli F., Balakay A.A., Filatov V.B. and others studied the bearing capacity of inclined sections under the action of transverse forces [9-12]. Experimental studies of strength under the action of transverse forces are considered in the works of Snezhkina O.V., Silantiev A.S., Tikhonov I.N. and others [13-15]. Aksenov N.B., Yakovlev S.N. and others studied the effect of deviations in the position of the working reinforcement from the design one on the strength of bending elements [16-17]. Campione G. and Zhuowei Wang A. established the influence of the coefficient of longitudinal reinforcement and the working height of the section on the shear strength of beam structures [18-19]. Kuznetsov V.S., Shaposhnikova Yu.A., Korchagin O.P., Merta I., Kolbich A., Kravanya S. and others studied the issues of optimizing reinforced concrete structures from the point of view of the economic component [20-23]. Dukhanin P.V., Radkevich A.V., Kuznetsova S.V. studied organizational and technological factors for the implementation of transverse reinforcement in beams [24-26].

Despite a fairly large number of works on the topic of optimal design of reinforced concrete beams, this direction has not been sufficiently studied. The combination of the pitch and diameters of the clamps, their different shapes, the bending radius of the clamp, etc., have a significant impact on the stress-strain state and on the technical and economic indicators of the structure. Therefore, a detailed consideration of this issue is of scientific and practical interest. The present study examines the features of the stress-strain state of reinforcement during bending of bars in the process of manufacturing clamps, studs and other bent reinforcing products. The paper specifies the limiting boundaries of bending angles in the manufacture of clamps or bent bars with different diameters of rods and mandrels. The work of the bars during bending is specified, subject to the condition of non-damage of the reinforcement. Reinforcing work includes such an important technological operation as the bending of bars. The implementation of the bend in the factory is preferable than on the construction site. At the plant, compliance with the necessary conditions for various technological operations is easier to control. When bending directly at the construction site, the requirements for this important technological stage are not always strictly observed.

There are some discrepancies in the existing regulations, in the recommendations for bending the rods. In Russia, the diameter of the mandrel is set depending on the diameter of the bent rod. In accordance with GOST 5781-82 "Hot-rolled steel for reinforcement of ferroconcrete structures. Specifications" and GOST 52544-2006 "Weldable deformed reinforcing rolled products of A500C and B500C classes for reinforcement of concrete constructions. Specifications" there are four groups of bar diameters, and according to SP 63.1330.2012 "Concrete and reinforced concrete structures. General provisions" only two groups. In European standards, BS 4466, BS 8110 and EN 1992-1-1, the minimum bending radius of the clamp is set in a similar way and depends on the plastic properties of the steels of the used rod classes. In the US code, ACI 318-05 and ASTM A82/A82M-07, the bend radius of the rods also depends only on the collar diameter (Table 1). A detailed comparison of the regulatory requirements for mandrels diameters and applied steel grades in different countries is presented by the authors in a previous paper [7].

Table 1. Regulatory requirements for mandrels diameters.

GOST 5781, GOST 52544-2006	
Nominal bar Size *d*, mm	**Minimum mandrel size *D***
≤12	5*d*
>12≤16	6*d*
>16≤ 25	8*d*
>25≤50	10*d*

SP 63.1330.2012		
Bar size *d*, mm	**Minimum mandrel size *D***	
	Plain bar	**Ribbed bar**
<20	2.5*d*	5*d*
≥20	4.0*d*	8*d*

BS 4466, BS 8110, EN 1992-1-1	
Bar size *d*, mm	**Radius bending *R*, mm**
8	16
10	20
12	24
16	32
20	70
25	87
32	112
40	140

ACI 318-05, ASTM A82/A82M-07	
Bar size *d*, mm	**Minimum mandrel size *D***
-	-
10-25	6*d*
29, 32, 36	8*d*
43, 57	10*d*

Note to Table 2. Designations: *d* – diameter of the bent bar (clamp); *D* – diameter of the mandrel.

The above circumstances indicate the need for the present research. The aim of the work is to study the stress-strain state of reinforcing bars during bending and to obtain the appropriate formulas and dependencies to clarify the possible boundaries of the use of mandrels for reinforcement of various classes and diameters.

The main objectives of this study were:

- clarification of the optimal diameters of mandrels when bending reinforcing bars;
- establishment of minimum diameters of mandrels when using various types and classes of reinforcement;
- identifying dependencies and establishing the degree of influence of various classes of reinforcement, the bending radius of the clamp, as well as the diameter

and class of the longitudinal reinforcement of the beam on the stress-strain state of the reinforcing bar.

2 Methods

In the presented work, the calculation-analytical method of research is used. The method is based on the analysis of the obtained results of relative elongations when using different ratios of the diameters of mandrels and bending bars. The study determines the possible limits of use for various classes of bars, where the relative deformations of steel do not go beyond the yield strength.

The main strength and deformation characteristics of steel are determined by the results of testing special specimens for tension and bending in accordance with the regulations (Figure 1, 2).

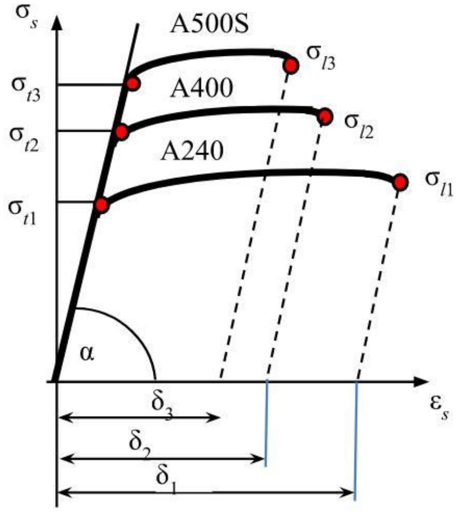

Fig. 1. Tensile diagrams of steels of classes A240, A400 and A500S.

These characteristics serve as the basis for calculations for the first and second groups of limit states and determine other requirements for the design of reinforced concrete structures. Based on these data, engineers judge the redistribution of forces in statically indeterminate structures, set the diameters of mandrels for bending rods, and so on.

In the Russian Federation, the deformation of steels is determined based on the results of tensile testing of samples according to GOST 1497-84 "Metals. Methods of tension test". Figure 1 shows the known tensile diagrams for steels of various classes A240, A400 and A500C.

The diagrams (Figure 1) show the elongation δ for various steels before failure of the test piece. Relative elongation is the increase in the length of the sample, which occurs after passing the yield point and before the destruction of the reinforcement. The test results of reinforcing samples are indicated in the certificate for each batch of reinforcing steels in accordance with GOST 23118-2019 "Building steel structures. General Specifications". Reinforcement can be made from steels of various grades. Steel grades differ in strength, plastic properties and chemical composition. The steel grade is assigned depending on the chemical composition and mechanical properties in accordance with regulatory documents:

- GOST 380-2005 "Common quality carbon steel. grades";

- ISO 630:1995 "Structural steels - Plates, wide flats, bars, sections and profiles";
- ISO 1052:1982 "Steels for general engineering purposes".

In practice, various designations of steel grades are used: St1, St5ps, St6ps according to GOST 380-2005; E 235-A (Fe 360-A) according to ISO 630:1995; Fe 490 according to ISO 1052:1982.

For example, according to GOST 380-2005, steel of category St1 is structural carbon steel of ordinary quality. The numbers from "0" to "6" indicate the conditional number of the steel grade.

Rebar manufacturers guarantee for St1 steel full relative deformations (relative elongations) δ not less than 25%, for St5 steel−δ≈(15÷17)%, and for St7 steel−δ≈(7÷9)%. Normalized values of deformation and strength characteristics of steels of classes A240, A400 and A500C according to GOST 34028-2016 "Reinforcing rolled products for reinforced concrete constructions. Specifications" are presented in Table 2.

Table 2. Indicators of deformation of reinforcing steels of various classes.

Reinforcement class	**Similar foreign steel grades**			**Yield strength $\sigma_т$, MPa**	**Tensile strength $\sigma_в$, MPa**	**Relative extension, %**			**Deformations, %**	
Russia	**USA**	**Great Britain**	**Germany**			δ_5	$\delta_{\rangle}$	δ_{max}	**at $\sigma_s=R_{sn}$**	**at $\sigma_s=R_s$**
A240	A283(A) K01804	4360-40B Fe360B	1.0036 Fe360B	240	380	25.0	–	–	0.120	0.105
A400	-	-	BSt420S BSt420S	390	590	16.0	–	5.0	0.2	0.175
A500C	Grade42	-	P275N	500	600	14.0	2.0	2.5	0.25	0.217

Note to Table 2. Designations: $\sigma_т$ – physical yield strength; δ_5 – relative elongation; δ – uniform elongation; δ_{max} – maximum elongation; R_{sn} – normative tensile strength of reinforcement; R_s – design tensile strength of the reinforcement.

In accordance with GOST 14019-2003 "Metallic materials. Bend test method" technological tests for cold bending consist in plastic deformation of samples by bending without changing the direction of the force until a given angle is reached (Figure 2). Samples of round, square, rectangular or polygonal sections are used for testing. As a result of the tests carried out, the ability of reinforcing steel to perceive deformations without

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violating integrity, that is, without the appearance of cracks, tears, delaminations, is established until a given bending angle is reached.

In order to avoid the destruction of the reinforcement during the manufacturing process, the value of plastic deformation in the bent bar should not exceed the limiting deformations of the reinforcing steel with a certain margin. The margin should be set to take into account future additional elongations under the application of external load, concrete creep and temperature effects during the operation phase. Ultimate deformations depend on the class and grade of steel (Table 2). This condition is especially important to observe when using reinforcing steels with small yield areas.

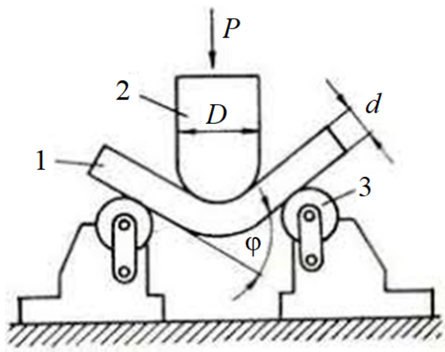

Fig. 2. The scheme of testing steel for bending in a cold state: 1 - test specimen, 2 - mandrel, 3 - track rollers.

The study considers reinforcing bars of classes A240, A400 and A500C in the bending stage. Rods of length L, without prestressing, with diameter d are considered. Reinforcing bars are bent to form clamps of a closed profile and subsequent use as transverse reinforcement in the section of a linear reinforced concrete element (beam). Figure 3 shows a diagram for determining the deformation of reinforcement during bending.

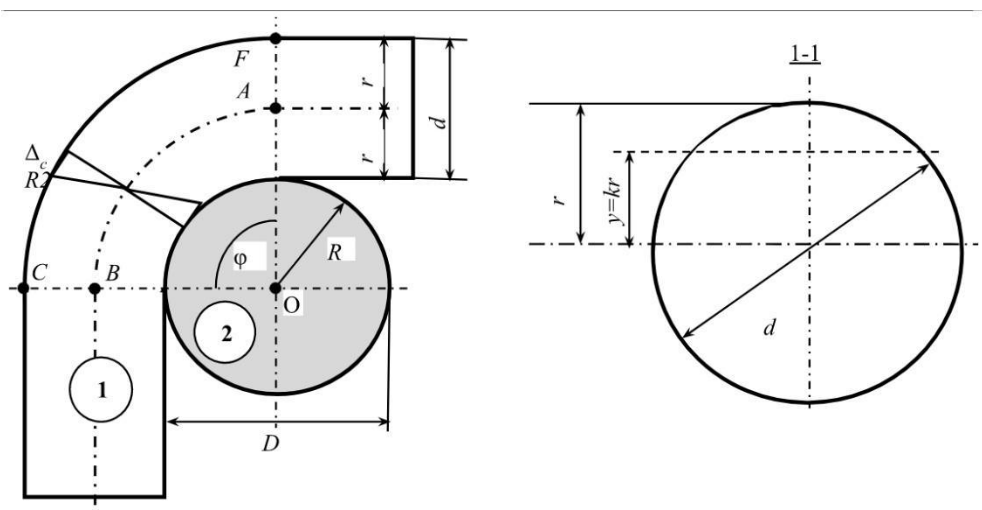

Fig. 3. Scheme for determining the deformation of a reinforcing bar during bending: 1 - rod, 2 - mandrel.

When a reinforcing bar is bent around a mandrel, the lengthening (or shortening) of the fibers of the bar is determined by the difference in the lengths of the arc of the center line and the arc at a distance x from the center line of the bar (Figure 3).

With reinforcing bar diameter $d=2r$, mandrel diameter $D=2R$, with bending angle φ, the length of the arc of the center line AB is $L_0=\pi\varphi(R+r)/180$, and the length of the arc CF is $L_1=\pi\varphi(R+2r)/180$.

The absolute elongation of the extreme fiber Δ at a distance r from the center of the section of the bending reinforcement is determined by the formula (1).

$$\Delta=L_1\text{-}L_0 = \pi\varphi((R+2r)\text{-}\pi\varphi(R+r))/180=\pi\varphi r/180 \quad (1)$$

The relative elongation ε of the extreme fiber at a distance $y=r$ can be expressed through the relative elongation

$$\varepsilon=\Delta/L_0=(\pi\varphi r/180)/(\pi\varphi(R+r)/180)=r/(R+r)=d/(D+d).$$

The relative elongation ε of the extreme fiber of the bent bar can be determined by formula (2).

$$\varepsilon=d/(D+d) \quad (2)$$

It can be seen from formula (2) that the relative elongation does not depend on the bend angle φ, but depends only on the bar diameter d and the mandrel diameter D.

When bending, the extreme fiber of the bent bar should not experience relative elongations greater than the limiting relative elongations of the steel class used, that is, ε≤™$_5$. Normative elongations of reinforcement ™$_5$: for class A240 − ™$_5$=25%, for A400 − ™$_5$=16%, for A500C − ™$_5$=14% according to table 2 in accordance with GOST 34028-2016. From formula (2), we can express the diameter of the mandrel D

$$D=(d\text{-}\varepsilon d)/\varepsilon=d/\varepsilon\text{-}d=d(1/\varepsilon\text{-}1)$$

Possible minimum allowable diameters of mandrels D for different diameters of bars d are determined in accordance with expression (3).

$$D=d(1/\varepsilon\text{-}1) \quad (3)$$

3 Results

The results of calculating relative elongations ε for the extreme fiber of a bent bar are shown in graphical form in Figure 4. Also in Figure 4, lines of standard relative elongations of reinforcement ™$_5$ are shown: for class A240 − ™$_5$=25%, for A400 − ™$_5$=16%, for A500S − ™$_5$=14% according to table 2 according to GOST 34028-2016.

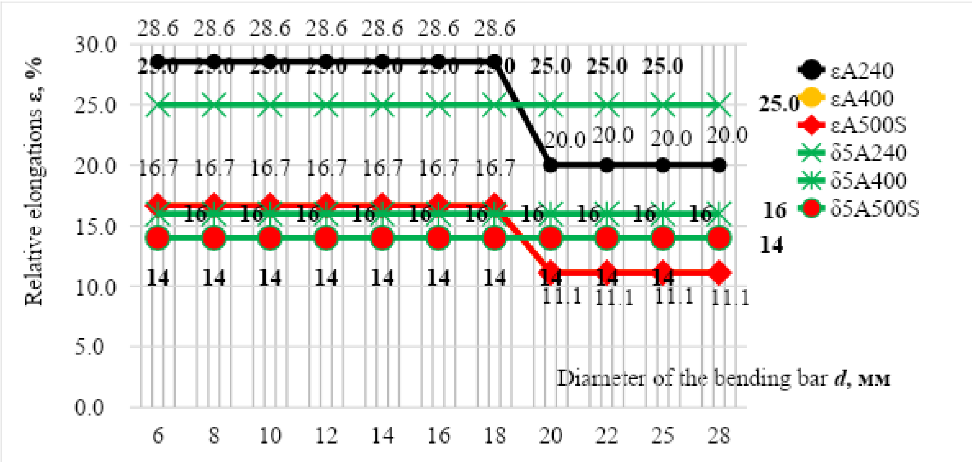

Fig. 4. Relative elongations ε of the extreme fiber of the bar with different diameters of the mandrel *D* and the bent bar *d* from reinforcement of classes A240, A400, A500S.

The graphs in Figure 4 show that the relative elongations ε of the extreme fiber of class A240 reinforcement are greater than for class A400 and A500S reinforcement. It can be seen from formula (2) that the relative elongation directly depends on the diameter of the bent bar *d*. Steel A240 is more ductile, so it is possible to use smaller diameter mandrels for it.

Relative elongations ε=28.6% for bar diameters *d*=6-18 mm made of class A240 rebar are 1.14 times higher than the normative ™$_5$=25% (Fig. 4).

Relative elongations ε for reinforcement of classes A400 and A500S in Figure 4 are the same, which is due to the same requirements for the diameters of mandrels for bars of a periodic profile according to SP 63.13330.2018.

The graphs of Figure 4 show that when moving from a diameter of *d*=18 mm to *d*=20 mm, there is a jump in the values of relative elongations ε, which is associated with the requirements for the mandrels used for bars with a diameter of *d*≥20 mm according to SP 63.13330.2018.

Recommended standards (SP 63.1330.2012) diameters of mandrels and maximum diameters of mandrels according to formula (3) for different diameters of bent bars *d* of classes A240, A400 and A500C are presented in tables 3, 4, and 5, respectively.

Table 3. Minimum allowable and recommended diameters of mandrels for plain bars of class A240 with various nominal diameters of bending reinforcement.

Nominal bar size *d*, mm	**Coefficient *k***	**Recommended mandrel diameter *D*=*kd*, mm**	**Normative elongations *ε*, %**	**Diameter mandrels *D*=*d*(1/ε-1), mm**
6	2,5	15	25,0	18,0
8	2,5	20	25,0	24,0
10	2,5	25	25,0	30,0
12	2,5	30	25,0	36,0
14	2,5	35	25,0	42,0
16	2,5	40	25,0	48,0
18	2,5	45	25,0	54,0
20	4	80	25,0	60,0
22	4	88	25,0	66,0
25	4	100	25,0	75,0
28	4	112	25,0	84,0

Table 4. Minimum allowable and recommended diameters of mandrels for bars of a periodic profile of class A400 for various nominal diameters of bending reinforcement.

Nominal bar size *d*, mm	**Coefficient *k***	**Recommended mandrel diameter *D*=*kd*, mm**	**Normative elongations ε, %**	**Diameter mandrels *D*=*d*(1/ε-1), mm**
6	5	30	16,0	31,5
8	5	40	16,0	42,0
10	5	50	16,0	52,5
12	5	60	16,0	63,0
14	5	70	16,0	73,5
16	5	80	16,0	84,0
18	5	90	16,0	94,5
20	8	160	16,0	105,0
22	8	176	16,0	115,5
25	8	200	16,0	131,3
28	8	224	16,0	147,0

Table 5. Minimum allowable and recommended diameters of mandrels for bars of a periodic profile of class A500S for various nominal diameters of bending reinforcement.

Nominal bar size *d*, mm	Coefficient *k*	Recommended mandrel diameter *D=kd*, mm	Normative elongations *ε*, %	Diameter mandrels *D=d*(1/ε-1), mm
6	5	30	14,0	36,9
8	5	40	14,0	49,1
10	5	50	14,0	61,4
12	5	60	14,0	73,7
14	5	70	14,0	86,0
16	5	80	14,0	98,3
18	5	90	14,0	110,6
20	8	160	14,0	122,9
22	8	176	14,0	135,1
25	8	200	14,0	153,6
28	8	224	14,0	172,0

The results obtained from tables 3, 4, and 5 are presented in graphical form in figures 5, 6, and 7, respectively.

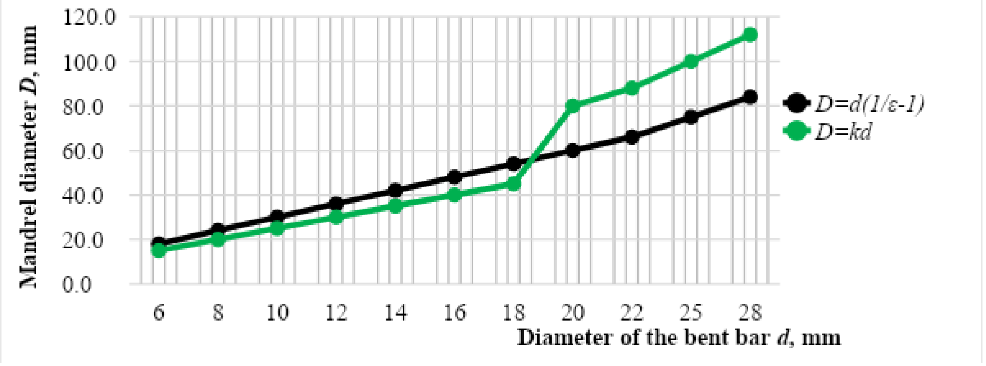

Fig. 5. The minimum allowable and recommended diameters of mandrels for class A240 plain rods with various nominal diameters of bending reinforcement.

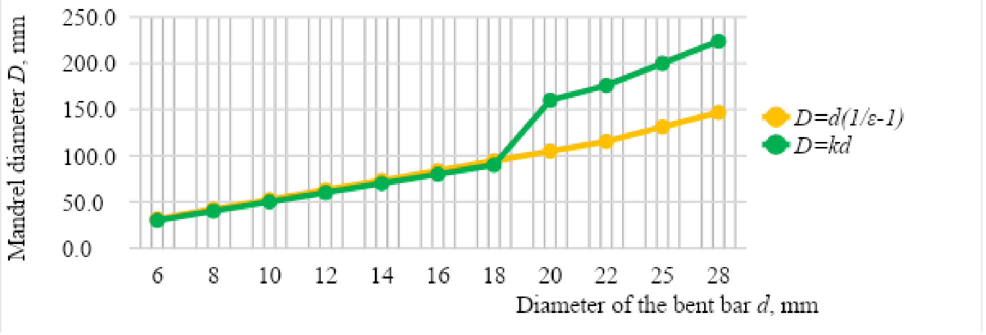

Fig. 6. The minimum allowable limit and recommended diameters of mandrels for rods of a periodic profile of class A400 for various nominal diameters of bending reinforcement.

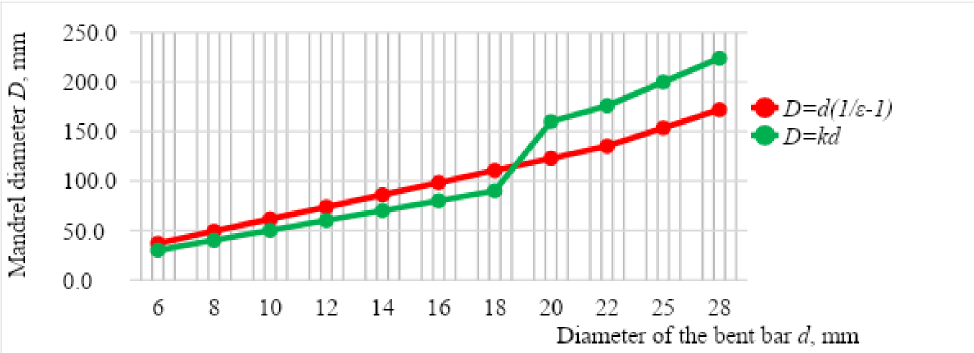

Fig. 7. The minimum allowable limit and recommended diameters of mandrels for rods of a periodic profile of class A500S for various nominal diameters of bending reinforcement.

From the graphs in Figures 5-7, it can be seen that for the entire range of steel classes under study (A240, A400 and A500C) for bent bar diameters $d \geq 20$ mm, the recommended mandrel diameters D according to the regulations are greater than the limiting mandrel diameters calculated based on the limiting relative elongation ™$_5$.

4 Discussion

The graphs in Figure 4 allow us to determine the limiting values of deformations in clamps by calculation when using different diameters of bars and mandrels.

Using the presented calculation and analytical method, it is possible to clarify recommendations on the minimum diameters of mandrels for bending rods in existing regulatory documents.

When choosing the diameters of the mandrels, it must be taken into account that when an external operational load is applied to the reinforced concrete element, the stresses in the clamps will increase. Therefore, when assigning the diameters of the mandrels, one should not assign the minimum possible mandrels, based on the maximum possible stresses in the bent bars. This circumstance can lead to the destruction of the bent rod, especially under the action of a long-term load.

5 Conclusions

1. An expression was obtained for calculating the possible limiting diameters of the mandrels D for various diameters of the rods d. The limiting diameter of the mandrel depends only on the relative standard elongation of the extreme fiber of the bent rod.
2. When assigning the diameters of the mandrels, it should be taken into account that the clamps will experience additional deformations due to the application of external operational loads.
3. The research results presented in the article can be used in practical work when assigning the optimal diameters of the mandrels when bending the rods.
4. The results obtained can be used to establish the minimum diameters of mandrels when using new types of reinforcement with different physical and mechanical properties.

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