Deformations and Stresses in the Structural Reinforcement when using Wending Rods

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Abstract

In monolithic construction, when manufacturing reinforcing articles on a construction site, technological requirements for the bending of rods may not always be observed. In various regulatory documents, there are differences in the technological requirements for this operation. The article presents the results of studies of the stress-strain state of reinforcement in the manufacture of clamps, pins and other products related to the bending of rods. Normative requirements and calculated values of limiting relative deformations for various classes of reinforcement and mandrel diameters are given. The recommendations of norms on the diameters of rods and mandrels in the manufacture of bent rods are checked and refined. The relative elongations or shortening of the fibers of the rod are determined by the difference in arc lengths of the midline and arc at a distance x from the midline. According to the results of the work, graphs of the distribution of the relative elongations of the rods are presented for different diameters of the mandrels as a function of the distance from the axis of the section. Plastic deformations develop practically over the entire cross-sectional area of the rod. The use of mandrels with radius less than R = 5r at the bending of armatures A400 and A500S is connected by the risk of cracking, delamination or destruction of the rod. The use of mandrels made from reinforcing bars A240 with mandrels of radius R = 2r is unacceptable, since edge deformations reach 35%, which exceeds the normative values and leads to the destruction of the rod. Also, the boundaries of the ratio of mandrel diameters for smooth reinforcement A240 and periodic A500S are presented. The results of this study can be used in practical work, as well as to establish the minimum mandrel diameters when using new types of reinforcement with other physical and mechanical properties.

Keywords: Bending angle, Bending rod, Mandrel, Monolithic construction, Reinforcement, Reinforcement clamp, Reinforcing bar, Reinforcing pin, Relative deformation, Rod armature, Steel stretching diagram
I. Introduction

In monolithic construction, when performing reinforcement work, it is necessary to bend the rods directly on the construction site, where the technical requirements of this important technological operation are not always observed, and there are discrepancies in the regulatory acts regulating the bending of the rods (SP 63.1330.2012, 2015; Kuznetcov V.S., Shaposhnikova Yu.A., 2016; Paille G.M., 2013; Seinturiere R., 2006).

For example, according to (GOST 5781-82, 2015; GOST 52544-2006, 2018) four groups of rod diameters are distinguished, and according to (SP 52-01-2003, 2015; Manual to SP 52-101-2003, 2005) two groups which is reflected in “Table 1”.

Table 1. Russian normative requirements for mandrel diameters

| Nominal diameter of reinforcement $d$, mm | Diameter of mandrel for bending $D$ | Diameter of reinforcement $d$, mm | Minimum mandrel diameter |
|------------------------------------------|------------------------------------|-----------------------------------|--------------------------|
| ≤12                                      | $5d$                               | <20                               | 2,5$d$                  |
| >12≤16                                   | $6d$                               | ≥20                               | 4,0$d$                  |
| >16≤25                                   | $8d$                               |                                    |                         |
| >25≤50                                   | $10d$                              |                                    |                         |

In European standards (BS 4466, 1989; BS 8110, 2010; EN 1992-1-1, 1998; Manual for the Design of Concrete Building Structures to Eurocode 2, 2006), the designation of the minimum bending radius of the reinforcement is set in a similar manner, and depends on the plastic properties of the steels used for the manufacture of reinforcement products and the diameters of the rods, as shown in “Table 2”.

Table 2. British normative requirements for mandrel diameters. Minimum former radii, bend and hook allowances

| Bar size, mm | Type and grade R and type and grade S, mm | Type and grade T and type and grade S, mm | Fabric complying with BS 4466, mm |
|--------------|------------------------------------------|------------------------------------------|---------------------------------|
| $d$          | $r$                                      | $r$                                      | $d$ $r$                        |
| 6           | 12    | 18    | 5    | 15 |
| 8           | 16    | 24    | 6    | 18 |
| 10          | 20    | 30    | 7    | 21 |
| 12          | 24    | 36    | 8    | 24 |
| 16          | 32    | 48    | 9    | 27 |
| 20          | 40    | 60    | 10   | 30 |
| 25          | 50    | 100   | 12   | 36 |
| 32          | 64    | 128   | -    | - |
| 40          | 80    | 160   | -    | - |
| 50          | 100   | 200   | -    | - |

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And in American norms (ACI 318-05, 2004; ASTM A82/A82M-07, 2013) the requirements for the radius of bending of the rods also depend on the diameters of the rods, three groups of rod diameters are distinguished, as shown in “Table 3“.

Table 3. US normative requirements for mandrel diameters. Minimum diameters of b

| Bar size $d_b$, mm | Minimum diameter |
|--------------------|-----------------|
| No. 10 through No. 25 | $6d_b$ |
| No. 29, No. 32, and No. 36 | $8d_b$ |
| No. 43 and No. 57 | $10d_b$ |

“Fig. 1“ shows the distribution of the minimum bending diameters depending on the diameters of the rods or wires in accordance with the requirements of regulatory documents of different countries: Russia, Great Britain and the United States.

The graphs show that all the normative documents considered limit the bending diameters depending on the diameter of the rods used.

The requirements of Russian and American standards on the establishment of bending diameters are close to each other and differ: for diameters $d=10-16$ by no more than 20%, for $d=18-25$ - by 30%, for $d=32-36$ - by 25%, and for $d=40-57^*$ - do not differ.

The recommendations of the British standards for setting mandrel sizes are more differentiated and significantly (up to 2 times) different from Russian ones, and the bending diameters largely depend on the type and class of reinforcement, as indicated in “Table 2“. This difference in British norms is explained by the variety of types of steels used for reinforcement of reinforced concrete elements.
Fig. 1. Minimum bending diameters depending on the diameters of the rods in accordance with the requirements of regulatory documents of different countries.

The paper deals with the features of the stress-strain state of the reinforcement in the bending of the rods during the manufacture of clamps, pins and other bent reinforcing articles. The safe radii of bending angles and ratios of diameters of rods and mandrels for reinforcing steels having different plastic properties, both domestic and foreign, are specified.

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II. Methods

For each of the types and types of rods used, there are standards for the steel used, depending on the manufacturing technology, application conditions and other. For example, “Table 4” shows the main types of steels and the documents regulating their performance.

Table 4. Analogues of Russian and foreign standards for steel

|                      | USA         | Great Britain | Germany   | Russia     |
|----------------------|-------------|---------------|-----------|------------|
| Structural           | ASTM A36    | BS4360/43A    | DIN 17100 | GOST 380   |
| Reinforcing          | ASTM A615   | BS4449        | DIN488    | GOST 5781  |
| Hot strips           | ASTM A569   | BS1449        | DIN 1016  | GOST 1050  |
| Cold rolled          | ASTM A366   | BS1449        | DIN 1623  | GOST 9045  |
| Galvanized           | ASTM A527   | BS/EN10143    | DIN/EN10143 | GOST 14918 |

The ability of reinforcing steel to perceive deformation without compromising integrity, i.e. without the appearance of cracks, tears, and bundles, is established by special tests. For reinforcing steel, they include testing a bar on a cold bend and reinforcement wire on the bend. The bend test consists of plastic deformation of samples of circular, square, rectangular or polygonal cross-sections by bending without changing the direction of the force until a specified bending angle is reached (GOST 14019-2003, 2015; GOST 12004-83, 2015; Bedarev A.V., 2014; Concrete and reinforced concrete - look in the future, 2014; Loganov V. A., Bogdanov V.P., 2008; BS 4466, 1989; BS 970-1, 1996; BS 970-2, 1988; BS 970-3, 1991; ASTM A82/A82M-07, 2013).

Relative elongation is an increase in the length of the sample, which occurs after the passage of the yield point and until the core itself is destroyed. The magnitude of plastic deformation in the rod, achieved during the bending process, should not exceed the limiting deformations of reinforcing steel, which depend on its class and brand “Fig. 2”, “Table 5”.

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This condition is especially important when using reinforcing steels having reduced flow areas.

Table 5. Examples of analogues of Russian and foreign brands of steels

| Russia | USA | Great Britain | Germany |
|--------|-----|--------------|---------|
| A240 St3kp | A283(A) | 1449-37/23CR | 1.0036 |
|         | A284Gr.D | 235JRG1 | 1.0036 |
|         | A570(33, 36) | 4360-40B | 1.0116 |
|         | A573Gr.58 | 4499-250 | Fe360B |
|         | A611Gr.C | Fe360B | Fe360D1 |
|         | K01804 | Fe360D1FF | K01804 |
|         | K02001 and etc. | HFS4 | K02301 |
|         | and etc. | HFW4 | and etc. |
|         | and etc. | S235J2G3 | and etc. |
| A240 St3ps | A284Gr.D | 1449-37/23CR | 1.0038 |
|         | A570(36) | 235JRG1 | 1.0116 |
|         | A573Gr.58 | 4360-40B | Fe360B |
|         | A611Gr.C | 4360-40D | Fe360D1 |
|         | GradeC | 4499-250 | RSt37-2 |
|         | K01804 | 722M24 | S235J2G3 |
|         | K02001 | Fe360BFU | USt37-2 |
|         | K02301 | Fe360D1FF | and etc. |
|         | and etc. | HFS3 | and etc. |
|         | and etc. | HFS4 | and etc. |
|         | and etc. | HFW3 | and etc. |
|         | and etc. | HFW4 | and etc. |
|         | and etc. | S235J2G3 | and etc. |
When bending around the mandrel “Fig. 3” the elongation (shortening) of the fibers of the rod is determined by the difference in arc lengths of the midline and arc at a distance \(x\) from the midline.

With the diameter of the reinforcing bar \(d=2r\), the diameter of the mandrel \(D=2R\) and the angle of bending \(\varphi\), the arc length of the midline \(AB\) is

\[ L_0 = \pi \varphi (R+r)/180, \]

and the arc length \(CE\) \(L_1 = \pi \varphi (R+2r)/180\).

The absolute elongation of the outermost fiber \(\Delta\) at a distance \(x=r\) is equal to

\[ \Delta = L_1 - L_0 = (\pi \varphi /180) r. \]  

(1)

The relative elongation of the outermost fiber \(\varepsilon\) at a distance \(x=r\) is equal to

\[ \varepsilon = \Delta/L_0 = (\pi \varphi /180) r/ \pi \varphi (R+r)/180 = r/(R+r). \]  

(2)

| St3sp (almost the same as St3ps) | A284Gr.D  
|                                      | A570(36)  
|                                      | A573Gr.58  
|                                      | A611Gr.C  
|                                      | GradeC  
|                                      | K01804  
|                                      | K02001  
|                                      | K02301  
|                                      | and etc.  
| 1449-27/23CR  
| 1449-37/23CR  
| 37/23HR  
| 4360-40B  
| 4360-40D  
| 4449-250  
| 722M24  
| Fe360BFU  
| Fe360D1FF  
| HFS3  
| HFS4  
| HFW3  
| HFW4  
| S235J2G3  
| and etc.  
| 1.0038  
| 1.0116  
| DC03  
| Fe360B  
| Fe360D1  
| RSt37-2  
| S235J0  
| S235J2G3  
| USt37-2  
| and etc.  
| 35GS  
| -  
| -  
| BSt420S  
| 25G2S  
| -  
| -  
| BSt420S  
| 32G2Rps  
| -  
| -  
| -  
| St3sp  
| See above  
| See above  
| See above  
| St3ps  
| See above  
| See above  
| See above  
| St3GPS  
| Grade42  
| -  
| P275N  
| S235J2G3  
| S275J2G3  
| S275JR  
| St44-3G  
| USt37-2G  

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Obviously, the relative elongation does not depend on the angle of bending $\varphi$, but only on the ratio of the diameters of the rod $d$ and the mandrel $D$. A diagram for determining the deformation of the reinforcement in bending is shown in “Fig. 3”.

![Diagram of deformation in bending](image)

**Fig. 3.** To the definition of deformation of the reinforcing bar at bending: 1 - rod, 2 – mandrel

Plastic deformations are determined when testing reinforcing specimens and are indicated in the certificate for each batch of reinforcing steels. It should be borne in mind that the reinforcement can be made of steels of various categories, which differ in plastic properties (GOST 14019-2003, 2015; GOST 12004-83, 2015; GOST R 54257-2010, 2011). For example, the armature made of steel St1 has complete relative deformations, at least 28%, St5 - (15÷17)%; and St7 - (7÷9)%. The normalized deformation values of steels A240 and A400 and A500S are presented in “Table 6”.

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Table 6. Indicators of deformability of reinforcing steels A240 and A400 and A500S

(GOST 5781, GOST 52544-2006)

| Reinforcement class | Elongation% | Elastic deformations % at |  
|---------------------|-------------|----------------------------|
|                     | The total $\delta$ | Uniform $\delta_u$ | $\sigma_{u}-R_m$ | $\sigma_{u}-R_s$ |
| A240                | 25          | -                          | 0.120            | 0.105            |
| A400                | 14          | 2                          | 0.2              | 0.175            |
| A500S               | 14          | 2                          | 0.25             | 0.217            |

III. Results and Discussion.

“Fig. 4” shows the distribution of the relative elongations of the rod and for different diameters of the mandrels.

The plots show that plastic deformations develop practically over the entire cross-sectional area of the rod. For steel A400 and A500S, rod extensions corresponding to the normative index of 14% are reached already at a distance $x=0.3r$ at the radius of the mandrel $R=2r$, at a distance $x=0.9r$ at $R=5r$ and $x=0.9r$ at $R=8r$. Thus, the use of mandrels of radius less than $R=5r$ or $(D=2.5d)$ in the bending of armatures A400 and A500S is associated with the risk of cracking, delamination or destruction of the rod.

Fig. 4. Elongation of rods for different diameters of mandrels

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It can also be seen that the use of mandrels made of reinforcing bars A240 with mandrels of radius $R=2r$ or $(D=2d)$ is unacceptable, since edge deformations reach 35%, which exceeds the normative values and leads to the destruction of the rod.

The graphs “Fig. 5” show the boundaries of the ratio of mandrel diameters for smooth reinforcement A240 and periodic A500S.

So for the A240 armature, the minimum value of the ratio of the diameter of the mandrel to the diameter of the rod $(k=D/r)$ and corresponding to a relative elongation of 25% $k=3$, which meets the requirements of the norms.

For the A500S armature, the minimum ratio $D/r$ corresponding to a relative elongation of 14% is $k=6$, which is more than the recommended ratio.

IV. Conclusions.

It should be noted that the requirements for Russian and American standards are close to each other, while the recommendations on the British standards from the others are significantly different. Such a difference between the British norms and the rest can be explained by the different physicochemical properties of the steels used to reinforce the jelly-concrete elements.

Based on the results of this paper, the safe boundaries of the bending angles and the ratios of the diameters of the rods and mandrels are specified. It has been established that the use of mandrels with radius less than $R = 5r$ for bending of A400 and A500S reinforcement can lead to the appearance of cracks, delamination or destruction of the rod, and for A240 valves, the use of mandrels of radius less than $R = 2r$ is inadmissible, since edge deformations reach 35 %, which leads to the destruction of the rod.

It should be borne in mind that during operation, the clamps of the compressed elements or compressed zones of the bent elements experience additional deformations associated with the lateral expansion of the concrete, which, together
with the initial relative elongations from the bend of the rod, can lead to its destruction. The results of the research presented in the article can be used in practical work, as well as to establish the minimum mandrel diameters when using new types of reinforcement having other physical and mechanical properties.

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