Optimization of flat-oval pipes and perspectives of their application in beam structures

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Abstract. A new technical solution for re-profiling round tubes into flat-oval ones with a ratio of 1 / 3,064 is presented, which increases their bending strength. The calculation of the optimal parameters of thin-walled sections of the flat-oval shape is given by an approximate method, the correctness of which is confirmed by testing from the standard profiles used. This calculation is repeated with respect to thin-walled sections of the oval shape. The whole diagram of changes in the design parameters of flat-oval and oval pipes is presented in the transformation of their cross-sections from vertical configurations to horizontal ones, including the transition through the outline of a circular shape. The comparative analysis of optimized cross sections of flat oval, oval and round tubes is carried out taking into account the elastic and elastic-plastic deformations of the structural material, where the length of the midline of the thin-walled section is taken as the dividing line between these deformations. The choice is substantiated in favour of flat-oval profile pipes due to their simpler shape including faces of constant curvature (flat and semi-circular), relatively low cost, lower height, greater compactness, higher resistance moment.

1 Introduction

Further optimization of flat-oval pipes is of practical interest in the case of beam systems, where flat-oval pipes can be no less rational and promising than in truss structures. This forecast is justified by the fact that pipes (round and profile) are in high demand not only in industrial and civil construction, but also in the construction of engineering structures, for example bridges [1]. Moreover, the importance of manufacturing pipes made of high-strength steels is growing [2]. In this case, the ovalization of round tubes allows to increase

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their characteristics in a certain direction (more often vertically) without increasing the consumption of the structural material.

2 Methods

A method for manufacturing oval shaped pipes is known, according to which a round, straight pipe after shaping and welding is oriented around the perimeter of the section at a certain angle with respect to the small axis of the oval (approximately 39˚32 '). After the orientation of the welded joint, the round tube enters the twin-roll stand, where it is ovalized with dimensions of the minor axis about 440 mm and large-650 mm (Fig. 1, a, b) [3]. This method ensures the location of welded joints in the zones of minimum bending stresses of oval pipes, but the ratio of the overall dimensions of their cross-sections (440/650 = 1 / 1,477) is different from the optimal parameters of the profiles with the maximum load-bearing capacity.

Another technical solution is known (taken as an analogue) in the form of a method of increasing the load-carrying capacity of a cylindrical pipe for bending, which consists in its reduction when heated to 600 ... 650º with the formation of an oval profile optimized by the criterion of the maximum load-bearing capacity, which is the largest (maximum) the moment of resistance (Figure 1, c) [4]. However, the production of a hot-rolled profile of an oval cross-section in this way has not yet been mastered by industry. The closest technical solution (taken as a prototype) to the proposed method is the method of obtaining from a cylindrical tube a circular cross-section, working on bending, an oval profile pipe optimized for the maximum resistance moment and flattened pipe distribution in the cold state by means of a jack system from within between two matrices [5]. The essence of the distinctive features of the prototype and analogue is that if the tubular profiles have oval-shaped cross-sections with a ratio of dimensions 1/ 2,99976… 1 / 2,99999 ≈ 1/3[6], then the resistance moments of these sections are maximal, and the profiles with such sections possess the greatest resources of load-bearing capacity for bending.

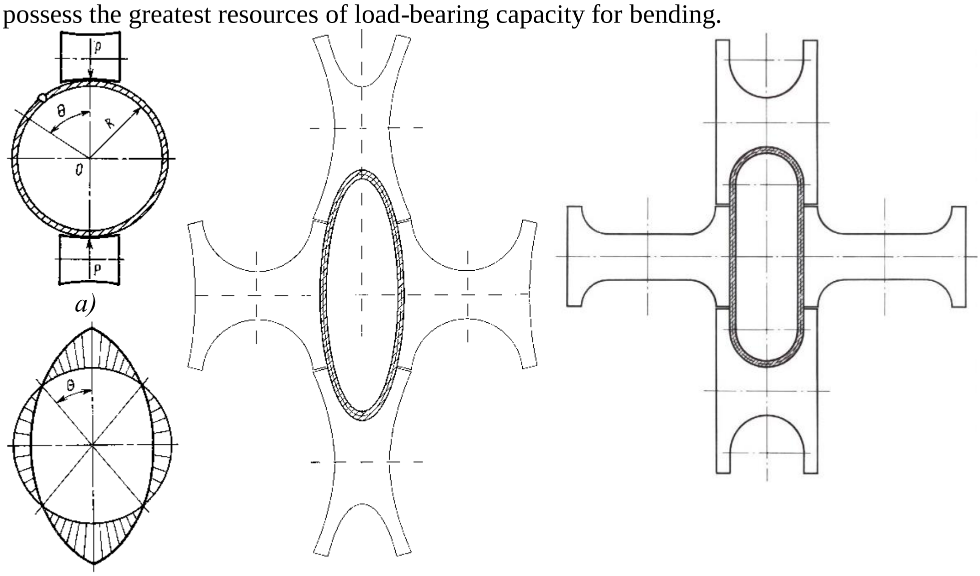


Fig. 1. Scheme for the ovalization of the round tube (a) and the bending moment diagram in the section for its unauthorized deformation (b), as well as the crimping scheme for the oval (c) and flat-oval (d) pipes

The main disadvantage of the prototype, as well as of other technical solutions, is the complicated form of the oval pipe, the surface of which is characterized by a complete absence of flat sections and the same lack of sections of constant curvature. This characteristic increases the complexity of both the manufacture of the pipe itself and its use in rod or beam structures, which is accompanied by a certain increase in costs.

3 Results

The technical result of the proposed solution is an increase in the load-bearing capacity of the tubular profile due to the increase in strength characteristics in bending, reducing the complexity of its manufacturing and use in rod or beam structures, as well as reducing costs for them. This result is achieved by the fact that in the method of re-profiling a round pipe, including technological operations to change the cross-section, this section is given a flat-oval shape with a ratio of overall dimensions 1 / 3,064 (Fig. 5, d) [7].
To derive this relation, it is necessary, using the formulas already tested, to find the extremely value of the moment of resistance, that is, its expression

$$W_x = (A^2/t)(0{,}333333/n^2 + 0{,}57/n + 0{,}0216012n - 0{,}13982)/(4/n^2 + 4{,}56/n + 1{,}2996) \quad (1)$$

differentiate with respect to the variable *n*, equating the derivative ($dW_x/dn = 0$) to zero, obtain an equation of the fourth degree

$$0{,}0280729n^4 + 0{,}1970028n^3 - 1{,}1191368n^2 - 1{,}98496n + 0{,}7599988 = 0$$

with roots

$$n_1 = -10{,}216734;\ n_2 = -1{,}7543858;\ n_3 = 0{,}3264179€;\ n_4 = 4{,}6271586$$

Of these roots, the third is of practical interest, the value of which can be rounded to

$$n = 0{,}32642 = 1/3{,}064 \quad (2)$$

and thus obtain the above ratio.

With $n = U/V = 0{,}32642 = 1/3{,}064$ a tubular profile with a flat-oval cross-section (a new technical solution) has the following parameters:

$$U = (A/t)(1/(2/0{,}32642 + 1{,}14)) = 0{,}1376069A/t; \quad (3)$$

$$V = (A/t)(1/(2 + 1{,}14 \times 0{,}32642)) = 0{,}4215640A/t; \quad (4)$$

$$n = 0{,}1376069/0{,}4215640 = 0{,}3264199 \approx 0{,}32642 = 1/3{,}064;$$

$$W_x = (A^2/t)(0{,}333333/0{,}32642^2 + 0{,}57/0{,}32642 + 0{,}0216012 \times 0{,}32642 - \\ - 0{,}13982)/(4/0{,}32642^2 + 4{,}56/0{,}32642 + 1{,}2996) = 0{,}0897905A^2/t \quad (5)$$

$$I_x = (0{,}1376069A/t)^3 t(0{,}0740286 + 0{,}785(1/0{,}32642 - 0{,}363)^2 + (1/0{,}32642 - 1)^3/6) = \\ = 0{,}0189529A^3/t^2 \quad (6)$$

The moment of resistance of the section has the greatest value, that is $W_x = W_{max}$ (Fig. 2, a).
With $n = U/V = 0{,}33333 = 1/3$ a tubular profile of the oval section (analog and prototype of the new solution) has the following parameters:

$$U = 2A/(3{,}14t(1 + 1/0{,}33333)) = 0{,}1592356A/t; \quad (7)$$

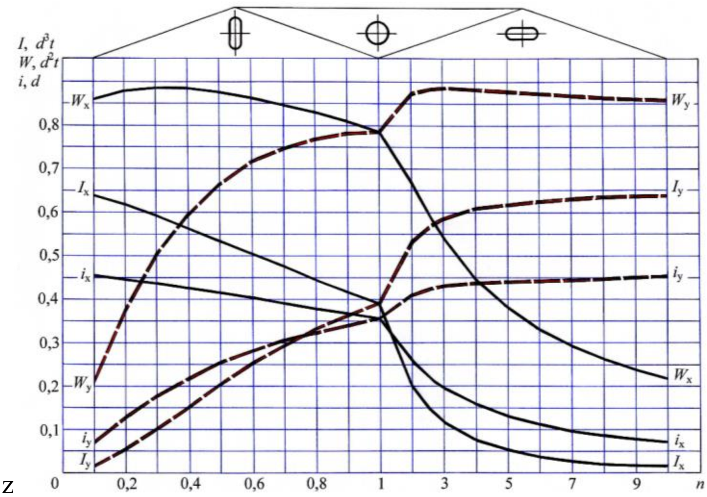
$$V = 2A/(3{,}14t(1+0{,}33333)) = 0{,}4777081A/t\,; \quad (8)$$

$$n = 0{,}1592356/0{,}477708 = 0{,}3333324 \approx 0{,}33333 = 1/3\,;$$

$$W_x = (3{,}14/16)(0{,}4777081(A/t))t(3\times 0{,}1592356A/t + 0{,}4777081A/t) = 0{,}0895703A^2/t\,; \quad (9)$$

$$I_x = (3{,}14/32)(0{,}4777081A/t)^2 t(3\times 0{,}1592356A/t + 0{,}4777081A/t) = 0{,}0213942A^3/t^2, \quad (10)$$

where the moment of resistance of the section has the greatest value, that is $W_x = W_{x,\max}$ (Fig. 2, b).



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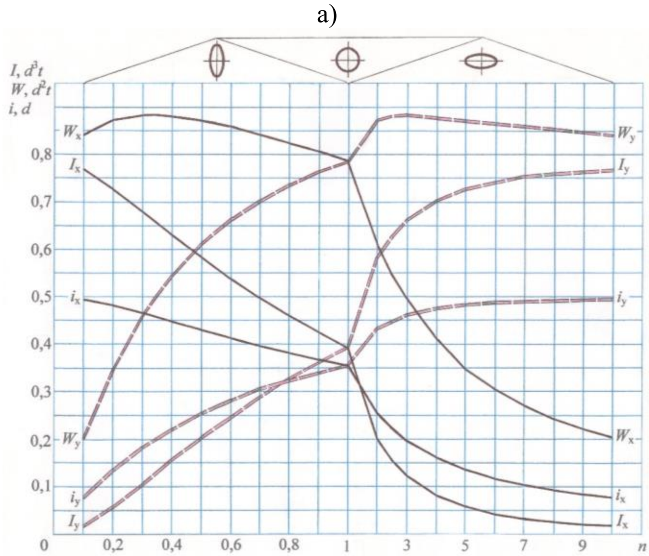
a)



b)

Fig. 2. Graphs of changes in the geometric characteristics of the sections of the flat-oval (a) and oval (b) pipes depending on the ratio of their dimensions (d - diameter of a circular tube along the midline of its cross section for $A = const$ and $t = const$).

Comparison of the results allows us to conclude that the design parameters of the prototype in absolute value exceed the calculated parameters of the proposed solution with the exception of the strength characteristic W_x:

$$\Delta U = 0{,}1592356 / 0{,}1276069 = 1{,}1571774$$
$$\Delta V = 0{,}4777081 / 0{,}421564 = 1{,}1331804$$
$$\Delta I_x = 0{,}0213942 / 0{,}0189262 = 1{,}1304012$$
$$\Delta W_x = 0{,}0895703 / 0{,}0897905 = 0{,}9975476$$

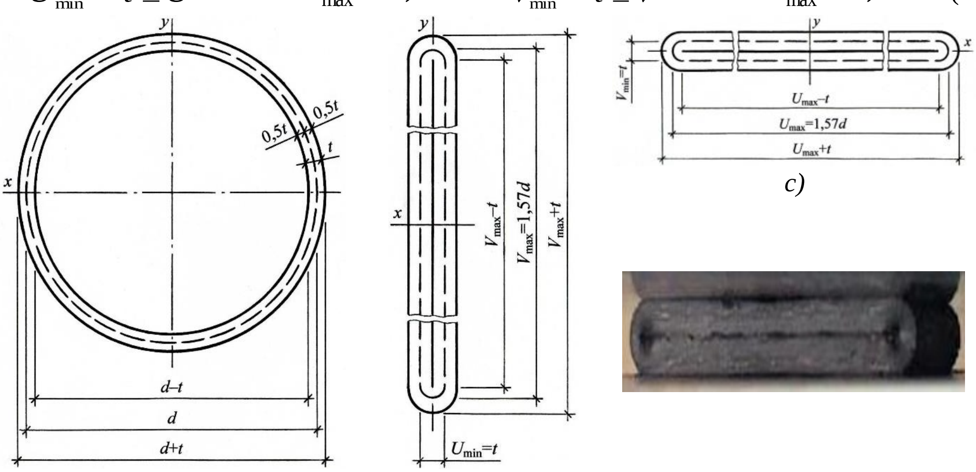
that is, under the given conditions, when $A = const$ and $t = const$, and $W_x = W_{max}$, for flat-oval pipes, the cross-sections are 13.3 ... 15.7% more compact than in oval ones, while in oval pipes the axial moments of inertia of the sections are 13.04% higher, and the moments of resistance 0.245% less than for flat-oval.

4 Discussions

All the calculations of the flat-oval and oval sections of the tubular profiles are performed under the assumption that they have the same initial blank (strip) with constant cross-sectional area ($A = const$) and constant thickness ($t = const$). This premise restricts the change in the dimensions of the frames, which are determined by the complete flattening of the tubular profiles, which, as applied to compliant supports in the form of annular tubes, is defined as the elasto-plastic deformation stage with curing (Figure 3) [8]:
- in general

$U_{min} = t \le U$ for $V \le V_{max} = 0{,}5A/t$ or $V_{min} = t \le V$ for $U \le U_{max} = 0{,}5A/t$; (11)
- in the case of a circular section

$U_{min} = t \le U$ for $V \le V_{max} = 1{,}57d$ or $V_{min} = t \le V$ for $U \le U_{max} = 1{,}57d$. (12)



a) b) d)

Fig. 3. Diagrams of tubular profiles: a - round shape; b - flat shape oblate in the vertical direction; c is a flat shape oblate in the horizontal direction; d - snapshot of deformation of a flexible support in the form of a tube of annular cross-section on the elasto-plastic stage with curing.

As an example of a promising implementation of a new technical solution, a three-sided lattice support with belts from flat-oval pipes (Figure 4, a) can be cited, and the case-free junctions of which are greatly simplified by flat faces [9]. An additional positive effect is quite achievable with the use of nodal eccentricities in such joints (Fig. 4, b), which are characteristic for constructions made of curved profiles (rectangular pipes).

In this case, the node eccentricities allow to limit the processing of the end edges of the rod elements of the grids by flat (straight and oblique) cuts, and also to optimize the flat-oval tubes for the belts by the criterion of equability, which is the same from the plane and in the plane of the lattice:

- for $e/U = 1/4$ and $n = U/V = 1/1{,}542$ (Figure 4, c)

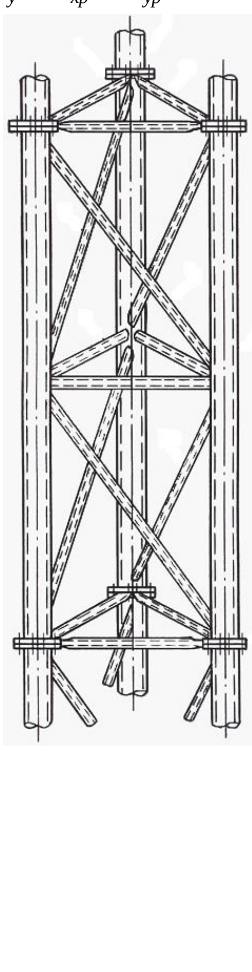
$$I_{xp} = I_{yp} = 1{,}0596U^3 t = 0{,}0142376 A^3/t^2\,; \qquad (13)$$

- for $e/U = 1/1{,}5774$ and $n = U/V = 1/3{,}064$ (Figure 4, d)

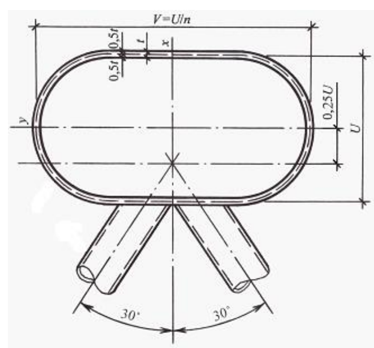
$$I_{xp} = I_{yp} = 5{,}8059U^3 t = 0{,}0151214 A^3/t^2\,. \qquad (14)$$

The obtained values of the axial moments of inertia of the flat-oval pipes exceed the corresponding values of the axial moments of inertia of the round tubes by a factor $(0{,}0142376...0{,}0151214)/0{,}0126779 = 1{,}123...1{,}193$, where the numerical value of the denominator is

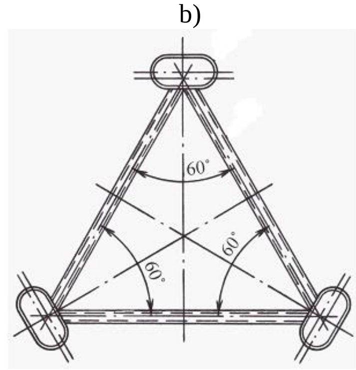
$$I_x = I_y = I_{xp} = I_{yp} = 0{,}3925 d^3 t = 0{,}3925(A/(3{,}14t))^3 t = 0{,}0126779 A^3/t^2\,.$$



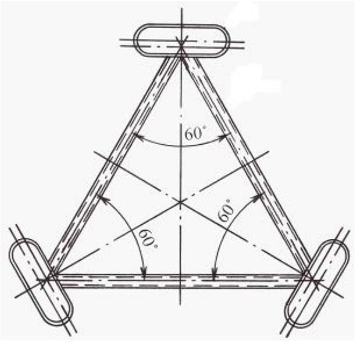
a)



b)



c)



d)

Fig. 4. Diagrams of triangular lattice support with belts from flat-oval pipes: a - axonometry of the fragment; b - cross-section of the belt with a gussetless abutment of the rod elements of the lattice; c - cross-section of the support with a ratio of the dimensions of the waist tubes 1 / 1,543; d - cross-section of the support with a ratio of the dimensions of the waist tubes 1 / 3,064

5 Conclusions

Thus, the obtained results of computational calculations and their comparison allow us to conclude that in order to increase the strength characteristic, the proposed solution is more effective than the prototype, since the growth of the moment of section resistance, other things being equal, is higher in the flat-oval profile than in the oval profile, and the overall shape of the cross-sectional shape is more compact. At the same time, as far as the oval section is larger than the flat-oval section, the growth of the stiffness characteristic, that is, the axial moment of inertia of the section, is approximately the same for it. If the large dimension is located vertically, then it can have a very significant practical significance, determining the dimensions of the building heights of beam structures, which makes the selection of a flat-oval cross-sectional shape for tubular profiles more preferable and justified. If we add to this that such a form is simpler, the complexity of manufacturing and application in designs is smaller, and the price is lower, then the positive effect of the proposed technical solution may be more visible and weighty. In conclusion, it should be noted that the above forms of cross sections are so attractive that they can be recommended not only for hollow (tubular), but also solid elements of bearing structures. Here we have in mind the oval section of the reinforcement for the reinforced concrete pillar of the power line supports [10], the long axis of which coincides with the direction of the maximum loads, and the lengths of the axes of this section are taken in proportion to the design loads.

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