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RESUDIAL STRESSES IN I-BEAMS AND ITS EFFECT ON RODS BUCKLING

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Abstract: Stability calculation of steel rods should consider residual stresses, as well as local imperfections (bends, buckling). Codes of EU, USA, PCR considering difference between welded and rolled I-beams on compression and compression with bending. Coefficient of longitudinal bending has values that consider the presence of different values of residual stresses for welded and rolled I-beams. Russian code for the design of steel structures (SP 16.13330) for conditionally centrally compressed rods does not distinguish between methods of I-beams production.

To determine residual stresses, a wide range of Russian profiles with different thin-walled was studied. Residual stresses for small-sized profiles were carried out by partitioning, for large I-beams - by drilling blind holes. The actual values of residual stresses in flanges and walls are established; most suitable curves for their approximation are selected. The actual shape of I-beams was also measured with a laser scanner. According to the results of curvature measuring, the limit and average values of local flanges deflection are established.

Considering experimental studies, FE-modeling of rods with residual stresses was performed for both rolled and welded I-beams. In addition to code eccentricities, local shape imperfections were modeled. It is established that rolled I-beams show higher values of critical forces than welded ones by 8-16%. This is true for steels C355 and C390 with a lambda-factor of more than 4, and for C255 with lambda-factor more than 3. According to the study, a coefficient is proposed that increases the bearing capacity of rolled I-beams for medium and large flexibilities.

Keywords: steel, stability, residual stress, section method, hole-drilling method, local buckling, rolled I-beam, welded I-beam, FE-modelling

ОСТАТОЧНЫЕ НАПРЯЖЕНИЯ В ДВУТАВРАХ И ИХ ВЛИЯНИЕ НА УСТОЙЧИВОСТЬ СТЕРЖНЕЙ

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Аннотация: Расчет стальных стержней на устойчивость должен учитывать наличие остаточных напряжений, а также наличие местных несовершенств формы (погибы, выпучивания). В нормах Евросоюза, США, КНР учтено отличие сварных и прокатных двутавров при работе на сжатие и сжатие с изгибом. Коэффициент продольного изгиба имеет значения, учитывающие наличие разных величин остаточных напряжений для сварного и прокатного двутавра. В отличие от указанных норм, российский свод правил по проектированию стальных конструкций (СП 16.13330) для центрально сжатых стержней не делает различия между способом производства двутавров.

Для определения величин остаточных напряжений был изучен широкий диапазон профилей российского производства с различной тонкостенностью. Остаточные напряжения для профилей небольших размеров проведены методом секционирования, для крупных двутавров – методом сверления глухих отверстий. Установлены фактические значения остаточных напряжений по полкам и стенкам, подобраны наиболее подходящие кривые для их аппроксимации. Также проведено измерение действительной формы двутавров лазерным сканером. По результатам анализа кривизны поверхности установлены предельные и средние значения местных погибей полок.

С учетом экспериментальных исследований выполнено КЭ-моделирование стержней с остаточными напряжениями как для прокатных и сварных двутавров из различных сталей. Кроме нормативных эксцентриситетов моделировались локальные несовершенства формы. Установлено, что прокатные

двутавры показывают большие значения критических сил, чем сварные на 8-16%. Это справедливо для сталей с С355 и С390 при условной гибкости более 4, а для С255 условной гибкости более 3. По результатам исследования предложен коэффициент, увеличивающий несущую способность прокатных двутавров для средних и больших гибкостей.

Ключевые слова: сталь, устойчивость, остаточные напряжения, секционирование, сверление отверстий, местная потеря устойчивости, прокатной двутавр, сварной двутавр, КЭ-моделирование

INTRODUCTION

In the studies of domestic [1, 2] and foreign authors [3, 4, 5] in the mid-20th century, it was established that residual stresses affect the performance of compressed steel bars. The following significant studies [6, 7, 8, 9] established the laws of development of residual stresses in I-beams, pipes, as well as other construction profiles. Based on the generalization of studies on the influence of residual stresses on rolled and welded sections, a document [10] was compiled. This document formed the basis for the creation of relevant provisions of Eurocode 3: Design of steel structures. Residual stresses along with other imperfections are considered in the standards for the calculation of structures by reduction factor φ for relevant buckling mode.

Let us compare the buckling curves for steel compressed rods according to the current standards. Figures 1, 2 show a comparison of the curves of the reduction factor φ from the current SP 16.13330.2016 "Steel Structures" (solid lines), from Eurocode 3 (European Union), from GB50017-2003 (PRC), from Steel Construction Manual 13th Edition (ASTM, USA). A comparison shows the following. Curves *a* and *b* follow practically the same trajectory and the deviation within the range of conditional flexibility from 0.4 to 4 is not more than 3% (0.8% on average), the curve c of SP 16.13330.2016 has a difference of up to 4.5% from the corresponding curve of Eurocode 3. The most advantageous in terms of material consumption are curves *a* and a_0. The sections of *a* type in SP 16.13330.2016 include closed pipes regardless of the method of production, and in Eurocode 3 are hot-rolled pipes, rolled I-beams in calculations in the plane of greater stiffness, as well as any I-beams in calculations in any direction from steel S460 (a_0). The curve a_0 gives φ values 6-7% higher than a from Eurocode 3 or from SP 16.13330.2016. This curve was introduced in Eurocode 3 based on several studies by European researchers in recent years [11, 12, 13, 14]. The Eurocode 3 accepts the most inefficient curve for column-type I-beams (height and width are the same). The difference in the performance of welded and rolled I-beams was identified and investigated abroad quite a long time ago [4, 8] and accounted for in the norms. SP 16.13330.2016 does not take into account the type of I-beam (column, beam, wide flange), the type of steel, the method of manufacture when evaluating the bearing capacity of centrally compressed elements. It also does not consider the direction of the design axes. I-beam in the plane of the flanges and in the plane of the wall is calculated using a single curve *b*. Eurocode 3 also has a curve *d*, which accounts for the negative effects of residual stresses in welded I-beams when calculating in the plane of the flanges, which are composed of two or more sheets.

In the range λ from 0.4 to 6 the value of the reduction factor φ according to ASTM is higher by 6.1% in comparison with curve b of Eurocode 3 and by 6.9% in comparison with curve b of SP 16.13330. The factor φ from GB50017-2003 (PRC) generally repeats the values of one from SP 16.13330. However, there is a separate curve for welded jambo-profiles, which considers the negative influence of welding stresses. These conclusions were drawn on the basis of several studies, including the investigation of I-beams made of high-strength steels [15, 16, 17].

It should be noted that modern RF standards have not been corrected in terms of specification of reduction factors φ for quite a long time. At

the same time, the values of factors in the 1980s were derived with regard to foreign experimental data on the values of residual stresses [1, 2]. The values of residual stresses were studied by some researchers in the 1980s after the beginning of the rolling mill for the production of wide-shelved I-beams in Nizhny Tagil [18]. Modern studies of residual stresses in rolled and welded sections were not aimed at updating the regulatory documents, but are devoted to important particular issues of the influence of residual stresses on the stress-strain state of certain structures. In particular, papers [19, 20] provide an investigation of stresses in tubular sections. In papers [21, 22] small I-beams and C-profiles are considered. Papers [23, 24] and etc. consider residual stresses from the standpoint of technological peculiarities of manufacturing.

Since there is no systematic research of residual stresses of I-beams in the part of their influence on stability of compressed beams, objectives and tasks of the current study are formulated. The objective of the study is to determine residual stresses in I-beams made of different steels produced in the Russian Federation, and to estimate the influence of residual stresses on the performance of compressed struts. One of the tasks is to estimate the difference between residual stresses in rolled and welded I-beams.

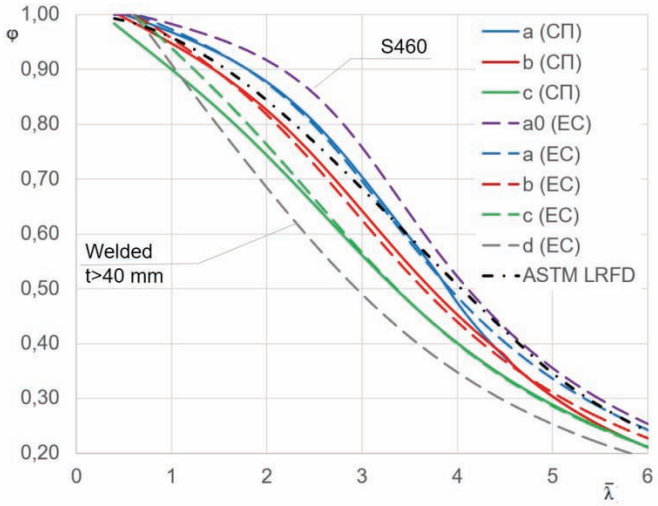


Figure 1. Graph $\varphi - \bar{\lambda}$ for SP 16.13330, Eurocode 3, ASTM

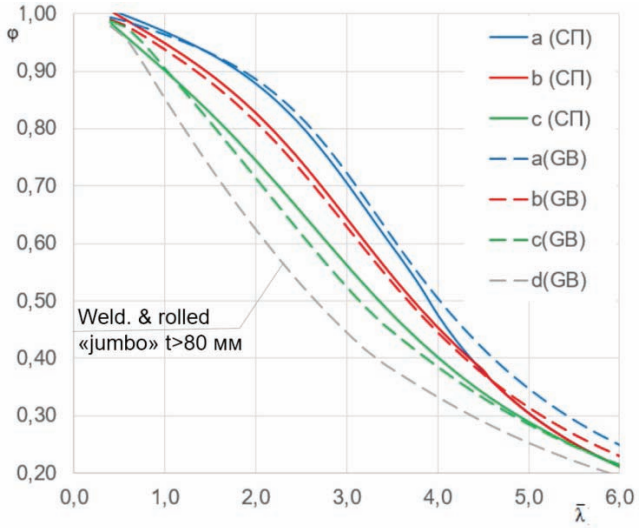


Figure 2. Graph $\varphi - \bar{\lambda}$ for SP 16.13330, GB50017-2003)

METHODS

A. Determination of residual stresses and real shape

To construct the residual stress diagrams, 10 samples selected from rolled I-beams produced in Russia according to GOST R 57837-2017 were investigated. Actual dimensions of the investigated sections and their mechanical characteristics are given in Table 1. In the table and further in the text the following designations are adopted: *L* is the length of the sample, *h* is the height of the I-beam, *b* is the shelf width, s is the wall thickness, *t* is the shelf thickness, h_w is the distance in light between the flanges, σ_y, σ_u are the yield strength and ultimate strength of steel according to test results. Relative lengths *L/h* of the studied samples are from 4.1 to 4.8. This means that the length of the samples did not affect the distribution of residual stresses. So, the determined residual stresses can be extended to all rod lengths (except for "short" ones, in which the *L/h* ratio is less than 3). As was shown in [3], the specimen length *L/h*>4 ensures that the residual stresses are unchanged when the specimen is cut out of the whole rod. Table 1 also shows that a wide range of profiles with different thinness *n=h/s* has been studied. The most "thin-walled" profiles are 15DK1 (A1) and 20Sh2 (A9), which have a parameter n of about 26. The least "thin-walled" profile is 20K8 (A6), which has parameter n about 13. The range of the studied profiles by parameter n covers almost all I-beams according to GOST R 57837-2017, which are used in structures as compressed rods. Such profiles belong to the K (column) type. The *h/b* ratio for them is approximately equal to 1 and ranges from 0.97 (20K1 A3) to 1.16 (20K8 A6). Also, for comparison were studied I-beam's type SH (wide-strip), for which *h/b* is approximately equal to 1.3 (20Sh2 (A9), 20Sh3 (A10). The specimens were made of C255 and C390 steels. The ratio σ_y/σ_u shows high plastic properties of steels and is from 0.63 (20Sh3 (A10) to 0.79 (15DK1 A1). The high plastic properties of the steels are also confirmed by the value of relative elongation from 30 to 39%, as well as the values of impact toughness values above 150 J/cm2.

Table 1. Studied profiles

Profile and steel	Dimensions based on measurement results (average values), mm						Profile's parameters				Steel characterisitics, MPa		
	L	*h*	*b*	*s*	*t*	h_w	*L/h*	*n = h/s*	*s/h*	*h/b*	σ_y	σ_u	σ_y/σ_u
1	2	3	4	5	6	7	8	9	10	11	12	13	14
A1 C255 15DK1	749	157	158	6.7	7.1	142.8	4.8	26.2	0.04	0.99	337	429	0.79
A2 C255 15DK3	689	161	153.9	9.2	11.3	138.4	4.3	20.0	0.06	1.05	301	443	0.68
A3 C255 20K1	832	192	198	7.2	9.9	172.2	4.3	30.2	0.04	0.97	280	423	0.66
A4 C255 20K3	822	201	200	11.1	13.6	173.8	4.1	22.7	0.06	1.01	273	422	0.65
A5 C390 20K3	816	200	199	10.3	13.6	172.8	4.1	22.7	0.05	1.01	403	539	0.75
A6 C390 20K8	971	231	200	19.8	28.9	173.2	4.2	13.0	0.09	1.16	383	531	0.72
A7 C390 30K7	1340	316	301	14.7	22.9	270.2	4.2	21.8	0.05	1.05	399	538	0.74
A8 C390 40K3	1659	409	401	16.5	23.6	361.8	4.1	25.4	0.04	1.02	403	563	0.72
A9 C255 20SH2	870	197	150	8.2	10.8	175.4	4.4	26.5	0.04	1.31	286	434	0.66
A10 C255 20SH3	845	202	150.5	9.8	12.7	177.3	4.2	22.7	0.05	1.35	266	422	0.63

Measurements of residual stresses in I-beams A3, A4, A5, A7, A8, A9 were performed by hole drilling method, in I-beams A1, A2, A10 - by sectioning method. I-beam A6 was tested by two methods to verify both methods and to control measurements.

The method of sectioning is based on cutting out of the specimen by two cross-section cuts a narrow fragment (temple), on the surface of which on the contour are previously glued strain gauges FLA-3-11 (24 to 36 pieces depending on the size of the I-beam). Strain gauge readings are measured throughout the cutting process. Fig. 3 shows a schematic diagram of the method. When the temple is cut, residual stresses are released in it. This causes changes in the readings of strain gauges. Based on these changes, the relative deformations ε in the measuring points and then the residual stresses are calculated assuming a linear stress state on the surface of the I-beam [25, 26].

The hole-drilling method is based on ASTM: E837 "Standard Test Method for Determining Residual Stresses by the Hole-Drilling Strain-Gauge Method". A strain-gauge socket (figure 4) is glued to the surface of the object under study and a hole is drilled in the center of the socket. Depending on the size of the I-beam, from 13 to 19 FRS-3-11 sockets were glued. The hole-drilling method does not release the strains from their own residual stresses completely. Therefore, the stresses cannot be calculated directly from the measured strains. It is necessary to have correction factors obtained computationally or experimentally. The computational method is based on the well-known solution of the problem of elasticity theory on the tension of a strip with a hole. The development of this solution using FEM is applied in the above-mentioned standard.

To identify the actual shape and dimensions of I-beams, surface scanning of specimens up to 5 m long was performed by HandyScan laser scanner. According to the results of scanning the surface maps of I-beams were constructed and analyzed. It was established that the curvature of the flange overhang is 1/100 0.5b in average and never exceeds 1/50 0.5b. For example, for the largest I-beam 40K3 the average value of the overhang curvature will be 2.01 mm, which was adopted in the further FE analysis).

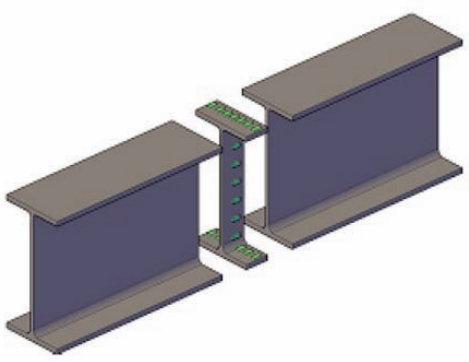


Figure 3. Sectioning method

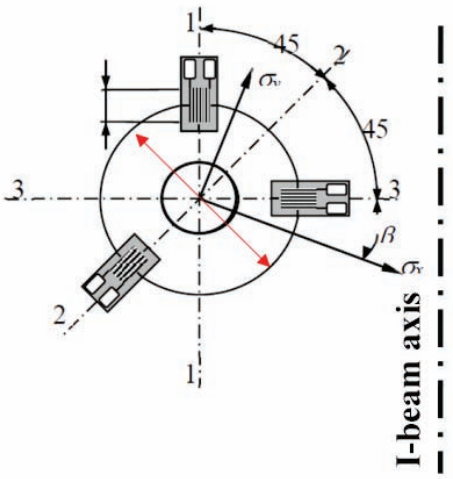


Figure 4. Socket of three strain gauges for the drilling method

B. Finite element modeling

A parametric finite-element model in Ansys Workbench was applied to solve the buckling problem of a centrally compressed I-beam profile. Solid finite elements in the form of hexahedrons ("Structural 3D Solid45") were used for modeling. Element size and mesh density were selected through successive iterative analyses. The first trial calculation was performed with a rough mesh, then a finer mesh was partitioned, the step was decreased by 20-30%. The results of the calculations were used to evaluate the change of critical load, if the difference of calculations with

different meshes in neighboring iterations was more than 0.5%, the mesh was reduced further and a new calculation was performed. The mesh densification was continued until the difference of critical loads in neighboring iterations was less than 0.5%. To specify the boundary conditions, the end nodes of the FE model of an I-beam were joined by an absolutely rigid finite element (one at each end), which had a hinged attachment at an eccentricity distance from the central axis of the profile. The eccentricity was set in the plane of least stiffness of an I-beam (a plane parallel to the flanges and passing through the center of gravity of the section). The compressive load was modeled by the movement of one hinged support along the initial axis of the rod. The modeling considered the elastoplastic properties of the steel. The σ-ε diagrams of the steels were assumed in accordance with SP 16.13330.2016 "Steel structures" in the form of piecewise linear functions. The plasticity criterion was taken as the von Mises criterion. Temperature fields were applied to the finite-element models of I-beams to set residual stresses. The temperature on the elements was set so that the final stresses in the I-beam corresponded to the test results for rolled I-beams and to the results of theoretical calculations for welded sections. An iterative type of solving a numerical problem by the Newton-Raphson method was used. This type of calculation is performed step by step according to the deformed scheme. The number of iterations for the considered models was from 30 to 80. The models were loaded until the appearance of necking in the diagram "longitudinal reaction of the support vs. displacement of the support". The maximum on this diagram was assumed to be the critical load of the model. Totally 324 models were created and calculated: 9 I-beam sections, given in table 1; for each section models with six slenderness ratios (λ =1; 2; 3,14; 4; 5; 6) were created; for each section and flexibility 3 kinds of steel were given for C255, C355 and C390; for each model residual stresses corresponding to rolled or welded version were specified. The general view of one of the models is shown in Figure 5.

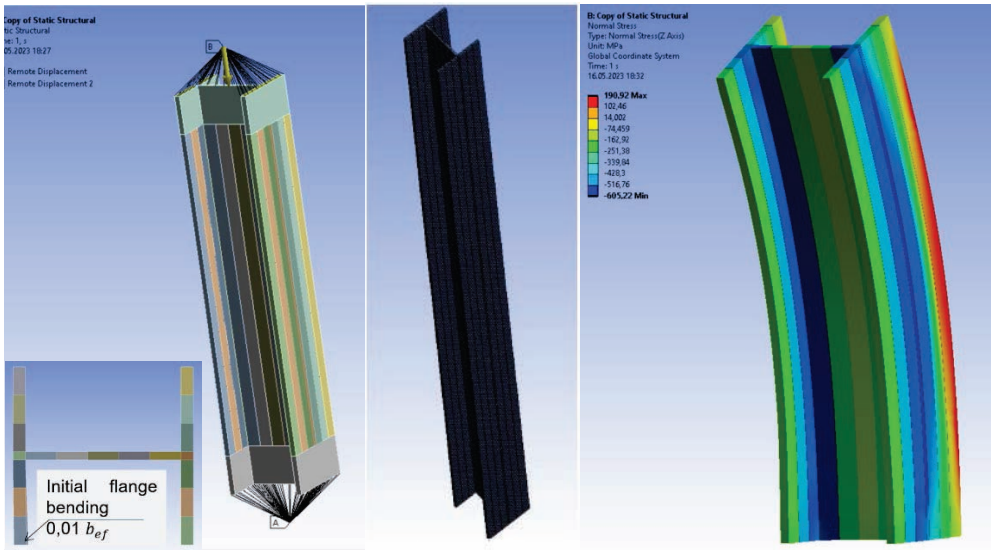


Figure 5. FE model of the rod

RESULTS AND DISCUSSION

A. Residual stresses

The measurement results of residual stresses are highly variable and should be analyzed by averaging and identifying general patterns. Averaging is performed by calculating average values from measurements of residual stresses in the similar elements at the same distance from the edges (for the flanges) or from the middle of the wall on the left and right surfaces. Figures 6 and 7 show the relative values of

residual stresses $\bar{\sigma}_{res}$ calculated with respect to the actual yield strength σ_y of a particular specimen $\bar{\sigma}_{res} = \sigma_{res}/\sigma_y$ in the relative coordinates $\bar{x}$ and $\bar{y}$. The coordinates are counted from the center of gravity of the section and calculated using the formulas формулам $\bar{x} = x_i/0{,}5b$ and $\bar{y} = y_i/0{,}5h_w$.. Fig. 6 and Figure 7 also show dashed lines for comparison the theoretical values of residual stresses for rolled I-beams taken from the authors Alpstein, Tebedge, Spoorenberg [8, 4, 12] and for welded I-beams according to [10, 13] (calculated for the weld with full penetration by automatic welding for profile-analogues).

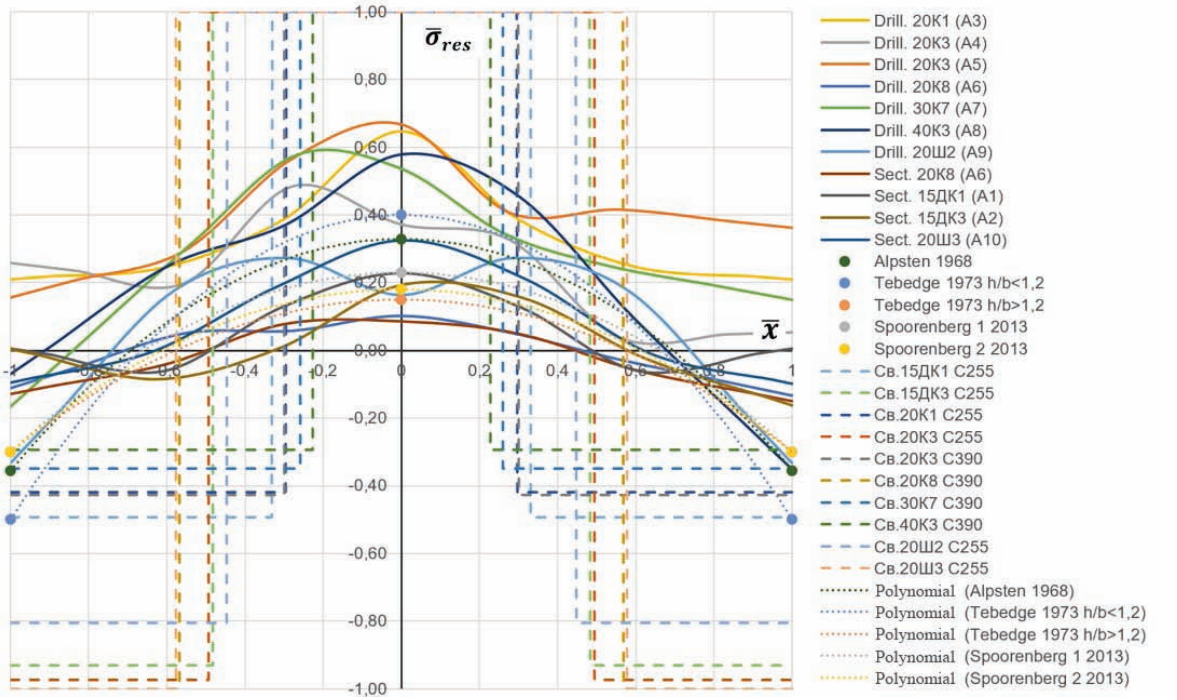


Figure 6. Measured residual stresses in I-beam flanges (solid lines)

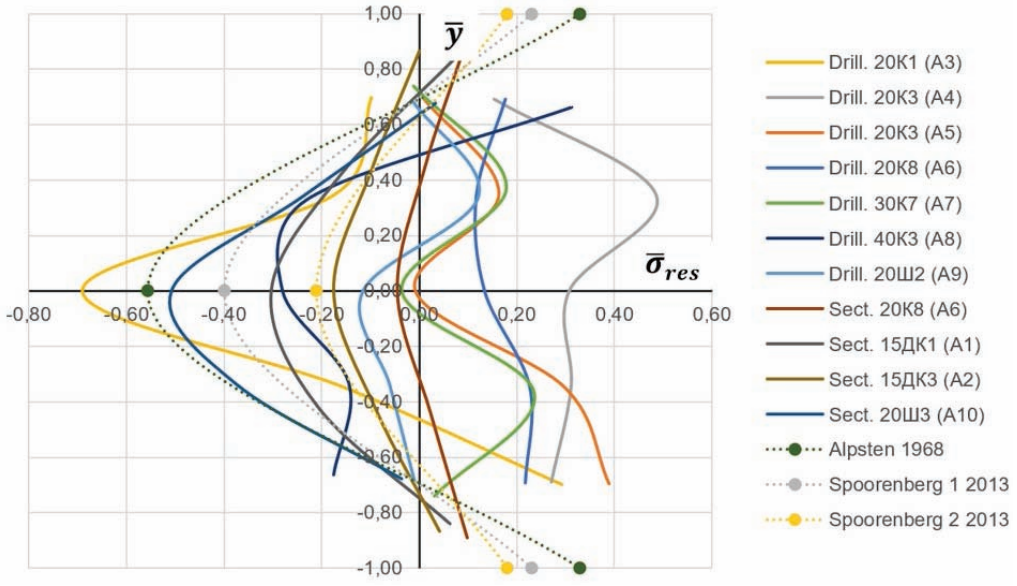


Figure 7. Measured residual stresses in I-beam walls (solid lines)

The best match with the actually measured stresses was demonstrated by the Spoorenberg dependences [12]. The closest to the theoretical value of residual stresses is the profile A9 20Sh2 (the difference in tensile and compressive stresses is 16 and 10%, respectively). The most far from the theoretical values is the most "thick-walled" profile A6 20K8 (the difference in tensile and compressive stresses is minus 171% and minus 125%, respectively). This means that the actual stresses are much lower than those predicted by theoretical studies. These differences are confirmed by two independent measurements of residual stresses in the I-beam. According to all considered theoretical dependences I-beams of Sh type (A9 and A10) most accurately describe the distribution of actual residual stresses. This is probably due to the fact that most of the profiles studied abroad refer to beams or wide-shelves. Correlation of the magnitude of deviations with the yield strength or thin-walled profiles is not revealed. The residual stresses in the wall have less correlation with the theoretical results (see Figure 7). For example, for some I-beams (A4 20K3, A7 30K7, A6 20K8 and others) the values of residual stresses which do not change sign and do not have parabolic form were recorded. This circumstance requires additional investigation and accumulation of statistical data for different I-beam producers. It should be noted that the distribution of residual stresses along the wall significantly depends on the production method as well as the position of the I-beam during cooling [4, 18]. Residual stresses in the wall practically do not affect the operation of the rod in eccentric compression [13, 14].

B. Performance of compressed rods

According to the results of the finite element analysis for buckling under central compression, the critical loads were calculated. On the basis of these loads the reduction factors were obtained by the formula 1, which is a modified formula 7 of SP 16.13330.2016 under the action on the rod of the critical force.

$$\varphi = \frac{N_{cr}}{\gamma_c A R_y} \quad (1)$$

where N_{cr} is the critical load based on the results of finite element modeling; A is the cross-sectional area by assortment; R_y is the design value of the yield strength of steel, $\gamma_c = 1$. According to the results of the analyses (Fig. 9), six dependences φ-λ were obtained for each type of section for three variants of steels and two versions of design (rolled, welded). Analyzing the obtained results, certain regularities can be noted. It is observed in all cases that I-beam section in welded version has lower factor φ than in rolled version. This can be noted on all the considered slenderness ratios and steel variants. The decrease in the load capacity is caused precisely by residual stresses, since the calculated models had the same geometric and mechanical characteristics and differed only in the initial internal stresses. During the detailed consideration of the stress-strain state of models and the estimation of influence of residual stresses a considerable influence of initial form imperfections on the character of stability loss and total bearing capacity has been noted. For welded I-beams, where residual stresses reach yield strength, distribution of stresses and strains over the section has an irregular character. That is, plastic deformations have a local character at the initial stages of loading. The maximum stresses are displaced from the outermost fibers inside the section. There are local stress concentrators which do not have significant influence for ideal shape of I-beam which is straight prism, but play significant role in the presence of local form imperfections. Figure 10 shows the graphs of φ-λ for an I-beam 30K7 as an example. The solid lines show the dependences for the rolled sections and the dashed lines for the welded ones. The red solid line is the curve for section type b in accordance with Table D.1 of SP 16.13330.2016. The detected deviations based on the results of detailed 3D scanning of the shape and dimensions of I-beam sections do not exceed the

limits set by the I-beam standards. Nevertheless, these deviations, taken into account in the FE modeling, had a significant impact on the nature of the buckling of the models. Local eccentricities in the flanges reached 2-3 mm, which caused additional bending moments and deformations of the section. In combination with local stress concentrators resulting from residual stresses, the eccentricities in the flanges led to local deformations having an avalanche-like character (Fig. 9). There was a local buckling, which immediately led to the loss of overall stability. This type of exhaustion of bearing capacity was most clearly observed in welded I-beams with relatively flexible flanges, for example, 20K1 and 15DK1. In rolled I-beams the loss buckling was also observed, but its effect on the final bearing capacity was less.

In the area of small slenderness ratios ($\bar{\lambda}$ ≈1÷3) the reduction factors obtained by numerical calculations are lower than the normative ones. This is characteristic of all welded and rolled profiles made of steel C355 and higher. In the area of medium slenderness ratios ($\bar{\lambda}$ ≈3÷6) the calculated reduction factors approximately coincide with the normative ones, and at large slenderness ratios ($\bar{\lambda}$ ≈6÷8) the bearing capacity according to the finite-element analysis is higher than that according to the normative calculation. The discrepancy between the results obtained and the method [12] is due to the fact that the numerical simulation takes into account not only the initial imperfections of the bars, but also local form imperfections and residual stresses. Residual stresses in combination with local form imperfections increase their influence with decreasing slenderness ratios. At large slenderness ratios, random eccentricities have a significant effect on bearing capacity, with profiles losing their overall stability earlier than local stability. The most unfavorable variations of residual stresses which can arise in the I-beam are taken into account in the FE modeling. The residual stresses obtained from the test results have been extended to the whole body of the profile, although in the real I-beam the residual stresses may be variable along the length and have less influence on the bearing capacity, being smaller in magnitude.

The analysis of the obtained $\varphi - \bar{\lambda}$ dependences shows that the factor φ decreases as the steel strength increases. This is observed in all the profiles considered both in the group of rolled I-beams and in the group of welded I-beams. Comparing the ratio of factors φ for different steels, a ratio $\frac{\varphi_{C390}}{\varphi_{C255}} = 0.975 \ldots 0.985$ is obtained at $\bar{\lambda}$=1. That is, the values of the coefficients are close enough. When $\bar{\lambda}$=6 the ratio $\frac{\varphi_{C390}}{\varphi_{C255}} = 0.715 \ldots 0.743$.. The decrease in the ratio $\frac{\varphi_{C390}}{\varphi_{C255}}$ with increasing slenderness ratio is explained by the fact that the conditional slenderness takes into account the strength characteristics of the material in a simplified form, and the given diagram of steel behavior according to SP 16.13330 is piecewise linear, but not curvilinear. A statistically reliable model of elastoplastic deformation for different steels in the section of transition from linear performance to yield point is required for more accurate modeling of I-beam operation depending on residual stresses, form imperfections and steel type. This issue is still open and requires further investigations.

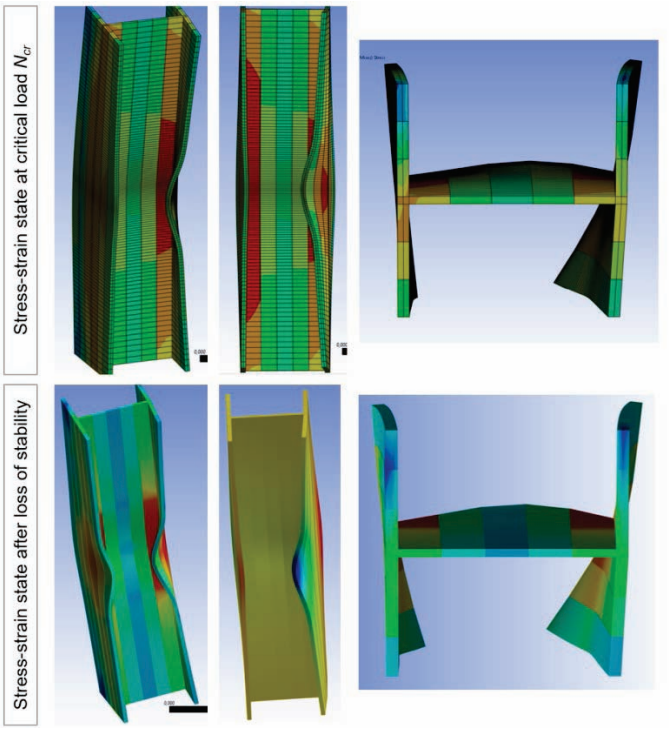


Figure 9. Stress-strain state for 30K7 profile at critical load (up) and after loss of stability (down)

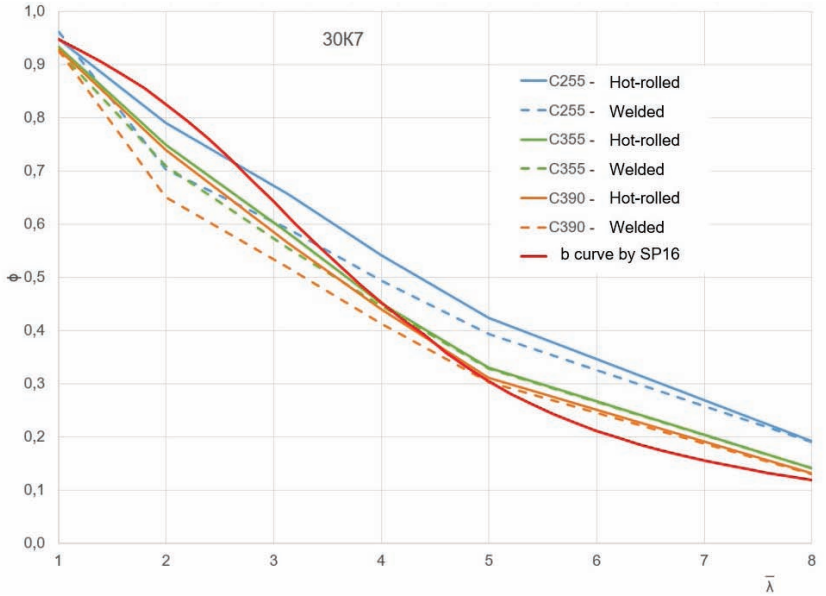


Figure10. Graph $\varphi - \bar{\lambda}$ for 30K7 profile

To evaluate the influence of I-beam section manufacturing method on its bearing capacity under central compression, it is necessary to consider the change in bearing capacity of sections of the same geometry and steel, but with different design - welded and rolled. For this purpose, let us analyze the ratio of the corresponding critical forces $N_{cr.Roll}/N_{cr.Weld}$ on the range of considered slenderness ratios $\bar{\lambda}$ (figure 11 - example for I-beam 30K7). The graph $\frac{N_{cr.Roll}}{N_{cr.Weld}} - \bar{\lambda}$ has a noticeable maximum in the range $\bar{\lambda} = 2 \div 4$, and this is typical for all the considered profiles and steel types. When

$\bar{\lambda} = 1$ the difference between the rolled version and the welded version is small. At high slenderness ratio $(\bar{\lambda} = 6 \div 8)$ the difference in bearing capacity of two versions is also not very large, the ratio $\frac{N_{cr.Roll}}{N_{cr.Weld}} - \bar{\lambda}$ does not exceed the value 1.03. The greatest difference of reduction factors is observed in the range of slenderness ratios $\bar{\lambda} = 2 \div 4$, at that for different profiles $\frac{N_{cr.Roll}}{N_{cr.Weld}} = 1{,}08 \div 1{,}16$. The highest values of $\frac{N_{cr.Roll}}{N_{cr.Weld}}$ are observed for profiles 40K3, 15DK3, 20Sh3.

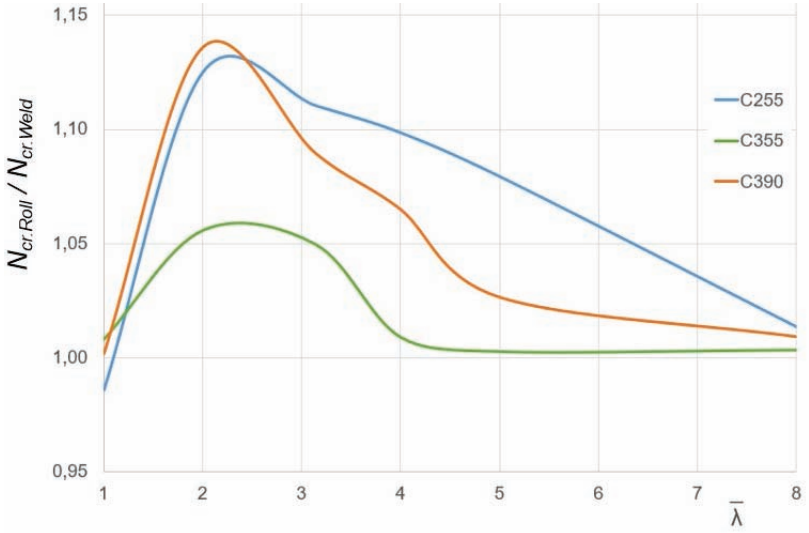


Figure 11. Graph $N_{cr.Roll}/N_{cr.Weld}$ for 30K7 profile

Let's compare the bearing capacity of the rolled I-beam, obtained from the results of numerical calculation, with the normative calculation according to SP 16.13330.2016. For this purpose let's consider the graph of the ratio $N_{cr.Roll}/N_{cr.Weld}$ as a function of $\bar{\lambda}$ (Figure 12 - example for 30K7). At small slenderness ratio $\bar{\lambda}$ = 1 the calculated values practically coincide with the normative estimate, the values $N_{cr.Roll}/N_{cr.Weld}$ are about unity. At slenderness ratio ratio $\bar{\lambda}$ = 2 the ratio $N_{cr.Roll}/N_{cr.Weld}$ is in many cases below unity, that is the numerical calculation of the rolled I-beam shows a lower carrying capacity than required by standards. The exception is the 20K type I-beams of C255 steel, for these cases $N_{cr.Roll}/N_{cr.Weld}$ is always greater than unity and constantly increases with increasing slenderness. For other profiles the growth of $N_{cr.Roll}/N_{cr.Weld}$ with increasing slenderness becomes true only when $\bar{\lambda} \geq 3$. In general, it can be said that the bearing capacity at numerical calculation is greater than the normative one for steels with strength characteristics C355 and higher at $\bar{\lambda}$ >4, and for C255 at $\bar{\lambda}$ >3.

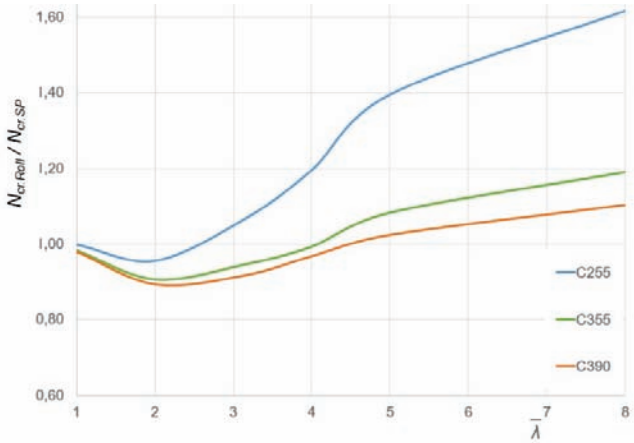


Figure 12. Graph $N_{cr.Roll}/N_{cr.SP}$ for 30K7 profile

C. Proposals for considering the effect of residual stresses in codes

The dependences "φ-λ " obtained by the results of the FE-analysis represent one of the worst-case scenarios of I-beams operation under

central compression when local form imperfections, the highest residual stresses and random eccentricities are acting in combination. For the calculation of standard structures, the normative checking according to SP 16.13330.2016 is sufficient. Reliability coefficients and behavior conditions laid down in the norms sufficiently prevent the influence of initial imperfections. Nevertheless, the results of the study showed that the rolled profiles behave more effectively in central compression than the welded ones. Based on the data obtained, in order to improve the normative methodology for calculation of I-beams in central compression, we can propose the coefficient k_{res}, increasing the bearing capacity of rolled I-beams for medium and large slenderness, in the following form:

$$k_{res(255)} = \begin{cases} 1; for\ \bar{\lambda} \leq 3 \\ 0{,}1\bar{\lambda} + 0{,}7; for\ \bar{\lambda} > 3 \end{cases} \quad (2)$$

$$k_{res(390)} = \begin{cases} 1; for\ \bar{\lambda} \leq 5 \\ 0{,}2\bar{\lambda} + 0{,}9; for\ \bar{\lambda} > 5 \end{cases} \quad (3)$$

The normative checking of the welded I-beam stability in central compression is recommended, as before, in accordance with paragraph 7.1.3 of SP 16.13330.2016. In turn, the test of buckling under the central compression of a rolled I-beam should be performed according to the formula (4), which accounts for a coefficient ofk_{res}:

$$\frac{N}{k_{res}\varphi R_y \gamma_c} \leq 1 \quad (4)$$

CONCLUSION

1. A study provides the results of investigation of actual residual stresses in rolled I-beams. Measurements of residual stresses were carried out on the entire range of rolled sections of the Russian Federation (GOST R 57837-2017) by proven methods: sectioning and drilling holes. The patterns of residual stresses distribution in flanges and walls of rolled I-beams have been revealed.
2. The shape of rolled I-beams has been measured. It was found that the bending of I-beam flange after rolling averages 0.01 b_{ef}.
3. By the whole range of cross-sections of the Russian product range (GOST R 57837), as well as by the most widespread range λ (from 1 to 6) the FE-models taking into account imperfections of two-beam shape and distribution of residual stresses were created.
4. The difference between the performance of welded and rolled sections, caused by different distribution of residual stresses, is covered by the existing reliability coefficients laid down in the normative documents.
5. According to the results of investigations, it was established that the rolled sections of domestic production behave in compression more effectively than the welded ones.
6. The calculation of critical structures in order to increase the efficiency of steel consumption for small eccentricities, it can be proposed to use the coefficient k_{res}, which increases the bearing capacity of rolled I-beams according to equations (2) and (3).

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