ALLOWING FOR RESIDUAL STRESSES IN THE CROSS-SECTIONS OF COMPRESSED I-SHAPED COLUMNS DURING THEIR DESIGN

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ABSTRACT

A procedure has been developed for evaluation of the stress-strain state of I-shaped steel columns at all the stages of loading, including the hypercritical region. Design has been performed allowing for the fields of residual stresses, arising in the cross-sections of these columns.

Key words: *load-carrying capacity, I-shaped column, residual stresses, design*

Fabrication of metal structures and items, irrespective of the technological processes, invariably leads to development of residual stresses that later on affect the element performance under load. For this reason, the problem of residual stresses distribution in the cross-sections of I-shaped columns and their influence on the structure performance under load, is the subject of numerous investigations, both in FSU and abroad.

Study [1] gives the results of experimental investigations of the influence of the residual stress fields on the load-carrying capacity of columns loaded by compression, that have an I-shape in the cross-section. Longitudinal deformations (stresses) are determined in the median section of two kinds of samples, namely welded I-shaped elements and similar samples, subjected to high-temperature annealing. Deformations were measured with strain gauges located opposite each other (mean arithmetic value was used). The derived data were the basis for plotting the characteristic graphs of stress variation and led to the conclusion on the influence of inherent stresses on the load-carrying capacity of welded elements with medium values of slenderness ratio. The results of compressive testing of the columns showed that the load-carrying capacity of welded columns is lower than a similar value for the columns subjected to high-temperature annealing after fabrication. This is caused by a high level of residual compressive stresses in the welded column flanges.

The authors of [2] have conducted a series of tests of welded column samples of low-alloyed steel. Three types of samples were taken, namely those subjected to post-weld annealing (A), regular welded columns (W), samples with initial tensile stresses at the edges (R). During testing, it was found that their load-carrying capacity depends on the value and nature of distribution of residual stresses, as well as the shape of the samples cross-section. As was anticipated, W type samples had lower load-carrying capacity, because of the presence of residual compressive stresses in the flanges, compared to samples of type A and R, which had no residual compressive stresses in the flanges.

Study [3] describes the results of investigations, conducted to determine the extent of residual stresses influence on the value of critical load. Tested were the rolled and welded profiles, where the chords developed residual compressive stresses, as well as columns with deposits on the edges. Surfacing of the edges induced additional tensile residual stresses that acted simultaneously with the initial compressive stresses. During investigations it was found that at flexibility $\lambda = 80$, the load carrying capacity of the rolled samples was 145 tons, and in welded samples with the same cross-sectional area, it was 95 tons. In samples with deposited welds, the load-carrying capacity was 135 tons.

Study [4] gives the results of testing the columns made to determine the residual stress influence on their load-carrying capacity. Riveted and welded columns with the same cross-sectional area were tested. It was found that the load-carrying capacity of welded columns is lower than that of the riveted columns. This is attributable to the presence of high-level residual compressive stresses on the flange edges. As was anticipated, the values of tensile stresses in the region immediately adjacent to the weld, are close to the steel yield point, while the stresses at the flange ends reach the level of 1400 MPa.

The above research results allowed determination of the residual stress influence on the load-carrying capacity of columns loaded by compression, that are deformed in the plane of lower rigidity. Study [5] gives experimental data on the influence of residual stresses on the stability of columns of the I-beam and box profile at off-center compression. It was found that the columns with a weld of a smaller cross-section, are less susceptible to deformation. Lowering of the deformation susceptibility can be achieved by depositing beads on the column edges. Bead deposition can be replaced by heating the edges to the temperature higher than A_{c_3}.

The derived experimental data (this paper does not give the results of other studies) were the basis for developing in the Donbass Mining-Metallurgical Institute a procedure for determination of the stress-strain state in the sections of composite and rolled I-shaped columns, having residual stress fields, as well as a procedure of evaluation of the load-carrying capacity and deformation susceptibility of columns compressed with different eccentricity, allowing for the fields of residual stresses in their cross-sections. These procedures are based on the common principles and assumptions of the mechanics of deformable bodies, and allow determination of the parameters of the deformed column (reference points of the load–deflection diagram) at all the stages of the load application, also in the hypercritical (after achievement of the maximum on the state curve) region.

Solution of the problem of determination of the stress-strain state of the column in the explicit form is impossible, because of the presence of a greater number of the unknowns, than in the equilibrium equation. It is solved by the iteration method using a specially developed algorithm [6].

The procedure of evaluation of the load-carrying capacity of compressed I-shaped columns allowing for the presence of residual stresses of different kind was used in design of experimental samples [1 – 4].

Experimental data (absolute or relative values of critical forces) were compared with similar data, derived through computation. The ratios of theoretical values of the load-carrying capacity to experimental data, expressed by coefficient K_p, were subjected to statistical processing. A satisfactory fit of the magnitudes of the compared values was achieved. So, mathematical expectation of coefficient K_p in processing 75 results, turned out to be equal to 1.011, while the mean root square deviation was $\sigma = 0.05$. The given results are indicative of a sufficient reliability of the design procedure.

The above procedure was used to conduct a mathematical experiment, that allowed solving the following problems.

1. Determine the area of a rational application of the developed analytical equations.

2. Determine the extent of influence of different factors (strength properties of the material R_s, flexibility λ, kind and width d of the zones of the residual tensile stresses), developing in the cross-sections of I-shaped columns in welding or local heat treatment, on the values of the critical forces at eccentricities e of load application close to the random values.

3. Derive dependencies of the change of the coefficient of longitudinal bending $\varphi = f\ (\lambda, e, d, R_s)$ and using the procedures recommended by the standards, prepare the proposals on design of columns loaded by compression and having the residual stress fields.

When the first two problems were solved, more than 400 models of the columns were computed to find that:

1) influence of the stress fields on behaviour of columns under load for the entire range of variation of the material strength properties, is characterized by similar dependencies, namely the zones of residual tensile stresses, located at the chord edges, increase, and those located in the area of chord welds decrease the values of the critical forces;

2) significant discrepancies in the values of critical forces for the columns loaded by compression with chord welds are observed in the flexibility range from 40 to 100 (at columns flexibility below 40 and above 100, these discrepancies are minor). In the columns with the zones of tensile stresses on chord edges, the discrepancies in the values of critical forces begin at the flexibility higher than 40;

3) in the columns, in which the width of the zone of heating the chord edges up to the temperature, exceeding A_{c_3}, is more than 1.5 cm, the discrepancies in the values of critical forces, are negligible;

4) for the determined flexibility range ($60 < \lambda < 120$) the dependencies of variation of the longitudinal bending coefficient $\varphi\ (\lambda, e, d, R_s)$ are nonlinear.

The scope of mathematical experiment for solving the third problem was determined proceeding from the results of the performed computations, as well as allowing for the format of presentation of the longitudinal bending coefficient variation in SNiP II-23–81*. Altogether 504 column models were computed, for which the relative values of critical forces were determined. The derived data were subjected to successive approximation by the least squares method. First an approximation function was derived, allowing for the change of the longitudinal bending coefficient φ_0, provided the residual stress zones were absent. For the slenderness ratios $60 < \lambda < 120$ and design values of resistance of steel $200 < R_s < 400$ MPa, this function has the form of

$$\varphi_0 = (0.162\overline{R} - 0.254)\,\lambda_s^2 + (0.578 - 0.617\overline{R})\,\lambda_s + (0.36\overline{R} + 0.596), \quad (1)$$

where $\overline{R} = R_s/200$ is the relative resistance of steel (R_s is the design resistance of steel in megapascals); λ_s is the relative slenderness ratio of the column, equal to $\lambda/60$.

This was followed by successive approximation of additional summands in the equation of the longitudinal bending coefficient, derived as the difference between the relative values of load-carrying capacity at $d_k(d_p) \neq 0$ and $d_k(d_p) = 0$ (d_k and d_p are interpreted in explications to the equations given below). Additional functions were derived that have the following form:

for zones of tensile stresses at chord edges

$$\begin{aligned}\varphi_{d,\,1} = {} & [(0.776\overline{R} - 2.651)\lambda_s^2 + (9.44 - 2.993\overline{R})\lambda_s + (2.813\overline{R} - 7.38)]d_k^2 + \\ & + [(0.375 + 0.0933\overline{R})\lambda_s^2 - (1.577 + 0.105\overline{R})\lambda_s + (1.592 - 0.126\overline{R})]d_k,\end{aligned} \quad (2)$$

where $d_k = 2d_t/b_f$ (here d_t is the width of the HAZ, determined by a specially developed algorithm [6]; b_f is the flange width);

for chord welds

$$\varphi_{d,2} = [(0.0207\overline{R} - 0.0176)\lambda_s - (0.0221\overline{R} + 0.0024)]d_p^2 + \\ + [(0.015 - 0.041\overline{R})\lambda_s^2 - \\ - (0.0904\overline{R} + 0.0806)\lambda_s - (0.249 + 0.00454\overline{R})]d_p, \quad (3)$$

where $d_p = (k_f + \delta)/t_w$ (k_f is the weld leg; δ is the base metal penetration depth; t_w is the thickness of the I-beam wall).

Then, the relative load-carrying capacity (longitudinal bending coefficient) is

$$\varphi_f = \varphi_0 + \varphi_d, \quad (4)$$

where φ_d is determined by substituting the values of $\varphi_{d,1}$ or $\varphi_{d,2}$, found from equation (2) or (3), respectively, depending on the kind of the residual stress field.

The derived approximation functions were subjected to subsequent statistical processing to determine the mathematical expectation of coefficient $K = \varphi_f/\varphi_m$ (φ_f, φ_m are the relative values of load-carrying capacity of the columns, derived from equation (4), respectively. and during the mathematical experiment) and its mean root square deviation. As shown by the performed computations (a sampling of 504 values of φ_f and φ_m was processed), mathematical expectation of the coefficient was $K = 1.000845$, while its mean root square deviation $\sigma = 0.0153$. Considering, that at probability $P = 0.99$, the values of mean root square deviation σ are in the range of $\pm 2.6 \cdot 0.0153 = \pm 0.0398$, the recommendation was to assign the values of the longitudinal bending coefficients φ, allowing for correction factor $\gamma_d = 1.000845 + 0.0398 \cong 1.04$, i.e.

$$\varphi = \varphi_f/\gamma_d = 0.962\varphi_f. \quad (5)$$

Thus, the influence of the residual stress fields on the load-carrying capacity of compressed I-shaped columns, deformed in the lower rigidity plane, can be taken into account by multiplying the values of design resistance of steel R_s by the longitudinal bending coefficient, calculated by (2) – (5). For some values of variables $\overline{R}$, λ_s, d_k, d_p, the values of coefficients have been computed and tabulated [6]. Computations by the proposed equations can be performed in two variants, namely the specified geometrical parameters, strength properties of materials and patterns of the residual stress zones are used to determine the load-carrying capacity of the column (Tcentr-3 algorithm); assigned values of longitudinal force, strength properties of the material and patterns of residual stress zones are used to select the cross-sectional dimensions of a welded I-shaped element (Tzentr-4 algorithm).

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