A WAY TO PUT AN END TO AN UNJUSTIFIED OVERCONSUMPTION OF PLASTIC STEELS AND ALLOYS IN INDUSTRY

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ABSTRACT

On the basis of the energy-based criterion, an analytical mechanism has been developed for consideration and transformation of the qualitative characteristics of structural materials, namely, the margins of plasticity and strain- and low-temperature hardening, into the design ones. The relationship established between the strain hardening margins of materials and their strength reserves has served as the basis for calculating differentiated increments to the standardized values of allowable stresses. This is equivalent to the differentiated and safe reduction of the safety factors depending on the level of the aforementioned margins for steels and alloys. Replacing the traditional stress-based method of strength analysis, which relies on the material strength characteristics only, by the energy-based one will, at last, put an end to the excessive consumption of a wide variety of ductile hardening and cold-resistant steels and alloys used in various branches of industry on a scientific basis rather than by way of compulsory reduction of the safety factors as it was done earlier only for austenitic steels and non-ferrous metals.

1 INTRODUCTION

The reduction in the metal consumption and costs of structures and machines without lowering the level of their reliability has been one of the main problems to the progress in mechanical and civil engineering at all times, and in attacking this problem, the development of a more accurate method of strength design is of vital importance as compared to the use of novel materials, manufacturing processes, and creation of more sophisticated structures.

As the use of various structural materials, especially ductile ones, was extended, the traditional stress-based method of strength design by allowable stresses proposed by Navier [1] more than a hundred and seventy years ago (even prior to the commercial production of steels and alloys), needed improvements in order to reduce the material consumption of structures. And those improvements were made.

Thus, for instance, in 1931, Loleit [2] proposed his strength analysis for reinforced-concrete structures by failure loads, which, after introducing corresponding design norms, made possible an essential reduction in material consumption. In 1955, using the method of ultimate states (the method of partial coefficients), the design norms developed under the guidance of Streletsky [3] for building structures (buildings and constructions) and later on for bridges and waterside projects were established and approved. Being based on the statistical study of the loading history of structures in operation, on consideration of the variability of mechanical properties of the materials used, and on the comparison of the levels of importance of various constructions, this method made it possible to exclude their critical states and unjustified excessive consumption of materials by introducing corresponding coefficients.

However, the performed modifications of the method of allowable stress-based calculations did not eliminate all its limitations. Thus, within various branches of machine-building industry strictly normalized safety factors are used up to now for a broad range of structural materials (materials with a wide range of the σ_u / $\sigma_{0.2}$ ratio) (Fig. 1). It means that the standardizing documents in force disregard the fact that numerous grades of steels and alloys differ appreciably

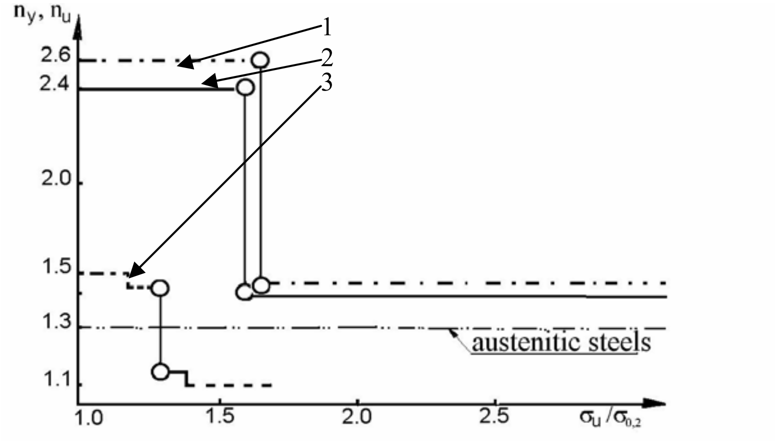

Figure 1: Safety factors as functions of the ratio of material strength characteristics in various branches of industry: *1* – in nuclear engineering, *2* – in mechanical engineering, *3* – in civil engineering.

in their characteristics of plasticity, hardenability, and fracture toughness. This gives no way of taking full advantage of real strength properties of ductile hardening materials that allow creating structures of higher reliability. For many materials of this type it would be logical to set differentially lower safety factors than the standardized ones. This would increase the values of design stresses accordingly.

This limitation being realized, to ensure efficient usage of at least the most expensive and scarce materials – austenitic steels and non-ferrous metals and alloys – more than two decades ago, in industrially developed countries, the safety factors for these materials were reduced intentionally, in a directive manner (due to the absence of a scientific justification), from 1.5 to 1.3 and lower. At the same time, other rather ductile hardening steels and alloys, whose number increased dramatically by the 80ies of the last century and for characterization of which the Prandtle diagram is not valid, are still used one might say wastefully.

Another essential limitation of the stress-based method made itself evident with the progress in cryogenic engineering when problems arose in the use of the safe portion of the low-temperature hardening of cold-resistant steels and alloys. As is known, the strength of materials at cryogenic temperatures increases considerably, whereas the plasticity and fracture toughness decrease and the embrittlement enhances. In this connection, the stress-based method does not allow the use of the low-temperature hardening of cryogenic steels and alloys impartially and safely.

2 ENERGY-BASED CRITERION AND PARAMETERS

To eliminate the above limitations, a new energy-based concept of determining allowable (design) stresses has been proposed. As a criterion of serviceability of the material, we take specific work of its plastic deformation being an integral value, which for a piece-wise approximation of the tensile diagram is determined as

$$W_u = (\sigma_{0.2(y)} + \sigma_u)\varepsilon_u/2, \quad (1)$$

where $\sigma_{0.2(y)}$ and σ_u are the yield strength and ultimate strength, respectively; and ε_u is the plastic strain.

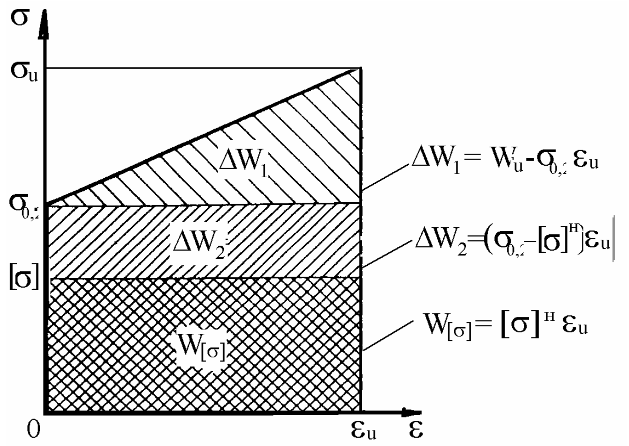

Figure 2: Conventional constituents of the specific work of plastic deformation.

Evaluating actual strength reserves for structural materials taking into account the presence of strain hardening and the fact that the allowable stresses are a certain part of the yield strength of the material (depending on the safety factor adopted in a given branch of industry), we represent the total value of the material energy absorption (eqn. 1) in the form of three specific components (Figure 2).

When comparing structural materials with different values of energy absorption reserves, it is more convenient to use generalized energy parameters. In this connection, an ideally hardening material, whose energy absorption related to strain hardening at a uniform strain, ε_u =1.0, is equal to its energy absorption without hardening $(\Delta W_i = W_i = \sigma_{0.2} \cdot 1.0)$ is taken as a reference material. Then we determine the generalized energy parameter β_1 that characterizes the capacity of any structural material for strain hardening and its corresponding strength reserve in the form of the following relationship:

$$\beta_1 = \frac{\Delta W_1}{W_i} = \frac{(\sigma_u - \sigma_{0.2})\varepsilon_u / 2}{\sigma_{0.2} \cdot 1.0} = (\sigma_u / \sigma_{0.2} - 1)\varepsilon_u / 2 . \qquad (2)$$

Analysis of the capacity of structural steels and alloys to hardening revealed that their energy parameter β_1 increases with increasing ratio $\sigma_u / \sigma_{0.2}$. In this case, the variation range of this parameter lies within the limits from 0 to 1, i.e., for β_1 > 0, the material has certain margins of plasticity and hardenability that should be used to increase the standard value of the allowable stress by determining the correction, which takes into account the strain hardening of the material.

The parameter β_1 is rather important because it correlates with the ratio of the limiting strength characteristics of materials, $\sigma_u / \sigma_{y(0.2)}$, and thus provides for their systematization by mechanical properties. In this way, the regularity established serves as an analytical basis when using the strength reserves of specific materials in calculations.

The energy parameter β_2, which characterizes the "unused" reserve of the material energy absorption depending on the value of the standard safety factor adopted for a given branch of industry, is determined as

$$\beta_2 = \frac{\Delta W_2}{W_i} = \frac{(\sigma_{0.2} - [\sigma]^{\text{H}})\varepsilon_u}{\sigma_{0.2} \cdot 1.0} = (1 - [\sigma]^{\text{H}} / \sigma_{0.2})\varepsilon_u. \quad (3)$$

For cryogenic temperatures, we determine the energy parameters β_1^t and β_2^t similarly to their determination at room temperature, but with the account taken of the change in the material energy absorption:

$$\beta_1^t = \Delta W_1^t / W_i = (\sigma_u^t - \sigma_{0.2}^t)\varepsilon_u^t / 2\sigma_{0.2}, \quad (4)$$

$$\beta_2^t = \Delta W_2^t / W_i = (\sigma_{0.2}^t \cdot \varepsilon_u^t - [\sigma]^{\text{H}} \varepsilon_u) / \sigma_{0.2}. \quad (5)$$

DETERMINATION OF ALLOWABLE STRESSES AT ROOM TEMPERATURE

The assumption that a relation exists between the margins of plasticity and hardenability of steels and alloys and their implicit strength reserves was the main hypothesis of the energy-based method for determining allowable stresses. This hypothesis proved correct when carrying out the systematization of structural materials by the strain hardening parameter β_1 resulting in a differentiated approach to revealing their strength reserves (Chechin [4-6]).

We determine allowable stresses by the energy-based method knowing the generalized energy parameters β_1 and β_2, which characterize the material energy absorption reserves, and calculating the corrections to the nominal value of allowable stresses:

$$[\sigma]^{\text{e}} = [\sigma]^{\text{H}} + [\Delta\sigma]_1 + [\Delta\sigma]_2. \quad (6)$$

Here, for different branches of industry, the magnitude of the initial (nominal) value $[\sigma]^{\text{H}}$ can be specified irrespective of the method under consideration.

Analytical relationships were obtained for the calculation of the corrections to the nominal allowable stress determined from the yield strength, 'y', or from the ultimate strength, 'u', in proportion to the energy parameters β_1 and β_2, and a detailed description of the procedure for the determination of the corrections is presented by Chechin in [5, 6]. These relationships have the following form:

$$[\Delta\sigma]_{1,\text{y}} = \frac{(\sigma_{\text{u}} - \sigma_{0.2})\beta_1}{2n_{\text{y}} / (n_{\text{y}} - 1)}; \qquad [\Delta\sigma]_{1,\text{u}} = \frac{(\sigma_{\text{u}} - \sigma_{0.2})\beta_1}{2n_{\text{u}} / (n_{\text{u}} - \sigma_{\text{u}} / \sigma_{0.2})}. \quad (7)$$

The second correction, $[\Delta\sigma]_2$, which allows taking into account the material strength reserve related to the excess of the yield strength over the chosen value of the nominal allowable stress, is determined as

$$[\Delta\sigma]_{2,\text{T}} = \frac{(\sigma_{0.2} - [\sigma]_y^H)\beta_2}{n_y}; \qquad [\Delta\sigma]_{2,\text{u}} = \frac{(\sigma_{0.2} - [\sigma]_{\text{u}}^{\text{H}})\beta_2}{n_{\text{u}}}. \quad (8)$$

We write eqn. (6) in the expanded form:

$$[\sigma]^e = \min\left\{ \frac{\sigma_{0.2}}{n_{\text{y}}} + \frac{(\sigma_u - \sigma_{0.2})\beta_1}{2n_{\text{y}} / (n_{\text{y}} - 1)} + \frac{(\sigma_{0.2} - [\sigma]_{\text{y}}^{\text{H}})\beta_2}{n_{\text{y}}}; \right.$$
$$\left. \frac{\sigma_{\text{u}}}{n_{\text{u}}} + \frac{(\sigma_u - \sigma_{0.2})\beta_1}{2n_{\text{u}} / (n_{\text{u}} - \sigma_{\text{u}} / \sigma_{0.2})} + \frac{(\sigma_{0.2} - [\sigma]_{\text{u}}^{\text{H}})\beta_2}{n_{\text{u}}} \right\}. \quad (9)$$

It is readily seen that in the case where the parameters β_1 and β_2 are equal to zero, the determination of allowable stresses conforms to the stress-based method.

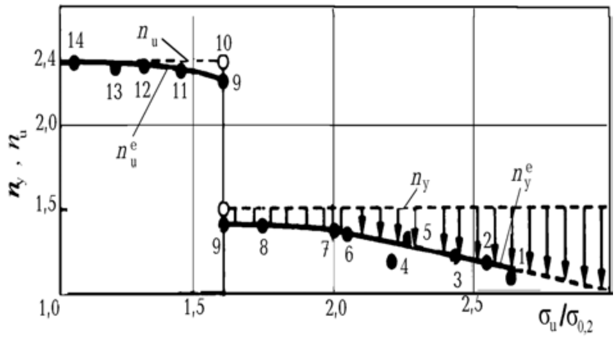

Figure 3: Differentiated safety factor n^e versus $\sigma_u/\sigma_{0.2}$. Points indicated the calculated values of n^e for the materials: *1* – 304SS, *2* – 0Kh14G18M, *3* – Kh18N12M3, *4* – 1Kh18N9T, *5* – 12Kh18N10T, *6* – 30Kh10G10, *7* – 2Kh13, *8* – steel 20, *9* – steel 3, *10* – Vst.3sp, *11* – A516, *12* – 15G2AFD, *13* – ÉP810, *14* – VT5-1kt.

DETERMINATION OF ALLOWABLE STRESSES AT CRYOGENIC TEMPERATURES

We determine these stresses as a sum of the initial nominal stress and corrections, which take into account the reserves of both strain and low-temperature hardening of the materials and the deterioration of their fracture toughness characteristics:

$$[\sigma]^{e,t} = [\sigma]^{H} + \left([\Delta\sigma]_1^t + [\Delta\sigma]_2^t\right)\beta_{J(K,\delta)}^t . \tag{10}$$

Similarly, we determine the corrections $[\Delta\sigma]_1^t$ and $[\Delta\sigma]_2^t$ (Chechin [5, 6]). In order to take into account the changes in the fracture toughness (crack growth resistance) at cryogenic temperatures, we introduce additionally the coefficient $\beta_{J(K,\delta)}^t$, which is equal to the ratio between the critical values of the J-integral at low and room temperatures ($\beta_J^{t} = J_{1c}^{t} / J_{1c}$), the ratio between the critical values of the stress intensity factors $\left(\beta_K^t = K_{1c}^t / K_{1c}\right)$, or the ratio of the critical values of the crack opening displacement $\left(\beta_\delta^t = \delta_{1c}^t / \delta_{1c}\right)$. Finally, eqn. (10) takes the form:

$$[\sigma]^{e,t} = \min\left\{ \frac{\sigma_{0.2}}{n_y} + \left[\frac{(\sigma_u^t - \sigma_{0.2}^u)\beta_1^t}{2n_y/(n_y - \sigma_{0.2}/\sigma_{0.2}^t)} + \frac{(\sigma_{0.2}^t - [\sigma]_y^H)\beta_2^t}{n_y} \right] \beta_{J(K,\delta)}^t ; \right.$$
$$\left. \frac{\sigma_u}{n_u} + \left[\frac{(\sigma_u^t - \sigma_{0.2})\beta_1^t}{2n_u/(n_u - \sigma_u/\sigma_{0.2}^t)} + \frac{(\sigma_{0.2}^t - [\sigma]_u^H)\beta_2^t}{n_u} \right] \beta_{J,(K,\delta)}^t \right\} \tag{11}$$

With the allowable stresses determined by the energy-based method, one can also estimate the adequate (safe) values of the safety factor for each material from the ratio

$$n = \frac{\sigma_{0.2(u)}}{[\sigma]^H + [\Delta\sigma]_1 + [\Delta\sigma]_2} = \frac{\sigma_{0.2(u)}}{[\sigma]^e} . \tag{12}$$

This means that the higher the correction value $[\Delta\sigma]_1$ for a specific material, the lower safety factor, as compared to the standardized one, can be assigned to it without reducing the safety of operating a structure of this material. Such an approach offers the possibility of substituting the safety factor values differentiated with respect to each material for the ones strictly normalized in different branches of industry.

The data presented in Fig. 3 illustrate the relation between the adequate safety factor values and the ratio $\sigma_u / \sigma_{0.2}$ showing their significant difference from the standardized ones (in mechanical engineering $[n]_y$ = 1.5), especially in the case of the materials for which the ratio $\sigma_u / \sigma_{0.2}$ > 2. The standardized value of the safety factor for these materials is set too high and does not allow us to use them efficiently.

To conclude, we may note that the method of determining allowable stresses based on the established relation of the margins of plasticity and strain and low-temperature hardening to the material strength reserves provides their differentiated increase (from fractions of a percent to some tens of percents) as compared to the values specified in the current standards.

Upon changing from the traditional force-based method to the energy-based one in engineering calculations, it will be possible to take into account the strength reserve of each specific material and thus provide a considerable saving of many ductile hardening and cold-resistant steels and alloys when developing metallic structures without reducing their safety level.

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