Strength and Resistance of Structural Steels and Materials

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Abstract. The paper presents basic information on determining of strength and resistance of structural steels and materials based on test results. The actual European standard EN 1990:2002 and related national standards CSN EN 1990:2004, and other are respected within the paper. The practical application of standard procedures is applied in determining the characteristic and design values of strength and resistance of structural steel S235 used for the production of welded test bars of the previous author's experimental researches. Experimental data on the actual geometric dimensions and material properties of the individual test bars enabled their detailed statistical evaluation. Subsequently, the characteristic and design values of strength and resistance of structural steels used for the production of test bars were determined. The characteristic and design values of strength and resistance determined in this way are compared with the standard ones, which for S235 steel contain valid standards for the design of steel structures.

1. Introduction
The steel structures are designed and made of metallurgical products - materials of suitable standardized shapes and dimensions (bars, sheets, strips), which are rolled from structural steels of various strengths, respectively strength classes. Adequate knowledge of the actual properties, especially the basic strength characteristics of structural steels, is one of the most important prerequisites for reliable and economical design of steel structures.

The basic strength characteristics of structural steels are generally considered to be the yield strength $f_y$, resp. $R_y$ and tensile strength $f_u$, resp. $R_m$ from the point of view of practical design. The strength characteristics of structural steels $f_y$ and $f_u$ depend on a number of random variables. For practical purposes, however, they are determined and standardized by concrete values. The determination of the standard values of the yield strength $f_y$ and the tensile strength $f_u$ of the recommended structural steels and materials must therefore have a probabilistic basis [1-3].

The strength of structural steels is influenced by the production itself - chemical composition and technological process. The strength of construction materials is also partially affected by the rolling process. It is therefore not the same, but varies both in length and within the cross-sections of the rolled bars.

The situation can be even more problematic in the case of welded bars consisting of different construction materials from the point of view of strength uniformity. Here, in addition to the already
mentioned effects of different melts, rolling, different cross-sections and thicknesses, the strength properties can also significantly affect the welding process. The actual strengths of construction materials are also affected by their dimensions themselves, in particular by the dimensions of their cross-sections, which show certain deviations from the design dimensions. Of course, the actual dimensional deviations of the construction materials can be both positive and negative. Depending on this, dimensional deviations affect the inherent strength and resistance of the construction materials and thus the load-bearing capacity, resp. resistance and reliability of steel bars and structures [4].

From the above it is clear that it is necessary to distinguish between the strength of structural steels and the strength, resp. resistance of structural materials and cross-sections of bars, which also takes into account their possible dimensional deviations. For the design and evaluation of the reliability of the steel structure, the strength of the materials and the material resistance of the bars used for its construction are decisive. The decisive strength characteristic of steel materials is the strength of the structural steels from which they are rolled, therefore the strength of the materials is generally equated with the strength of the structural steels themselves [5, 6].

2. Characteristic and design values steel structures strength and resistance

The strength characteristics of structural steels, in particular their yield strength f_y (R_y) and tensile strength f_u (R_m) are standardized according to individual strength classes on the basis of statistical evaluations of test results. Nominal or characteristic values of f_y and f_u for the individual recommended steels are given by standards for the design of steel structures. Within the European Union for it is mainly EN 1993-1-1:2006 and transformed national standards as are CSN EN 1993-1-1:2005, and other. The values of yield strength f_y and tensile strength f_u are more precisely specified in relevant material standards, as is EN 10025:2004 and transformed national standards CSN EN 10025:2005, and other.

In accordance with the applied method for the design of steel structures according to the limit states for the characteristic values of the yield strength f_y and the tensile strength f_u of structural steels, the failure probability P_y = 0.05 is generally accepted. For the calculation and assessment of the load-bearing capacity of steel structures, the design strength values of the structural steels and materials f_d are important. For the design values of strength f_d and resistance f_d, the failure probability P_d = P_Rd = 0.001 is generally accepted [1, 2].

The design strength values of structural steels f_d in the actual standards for the design of steel structures are no longer given, but are determined from the respective values of yield strength f_y, or tensile strength f_u and material reliability factors γ_M (γ_M0, γ_M1, γ_M2). Design strength

\[ f_d = f_y / \gamma_M, \ \text{consider} \ \gamma_M = \gamma_M0 \ \text{or} \ \gamma_M1 \]  
\[ f_u = f_u / \gamma_M, \ \text{considered} \ \gamma_M = \gamma_M2 \]  

Material reliability partial factors γ_M0, γ_M1 and γ_M2 are standardized. The individual γ_M coefficients according to the CSN 73 1401:1994 are contained in Table 1. The partial factors γ_M0 and γ_M1 have different values by strength steel class. The partial factor γ_M2 by previous standards has a uniform value of 1.3. These values were determined on the basis of a statistical analysis of the actual yield strength and tensile strength of Czech and Slovak structural steels, which were produced in the previous period [6]. Table 1 also shows the material reliability factors γ_M0, γ_M1 and γ_M2 according to the actual European standard EN 1993-1-1: 2005 and the subsequent transformed standard CSN EN 1993-1-1: 2006.
Table 1: Partial material reliability factors $\gamma_M$.

| Carrying capacity          | $\gamma_M$ | CSN 73 1401:1994 | EN 1993-1-1:2005 |
|---------------------------|-----------|------------------|-----------------|
|                           |           | S235  | S275  | S355  | S235  | S275  | S355  |
| Cross-sections 1, 2, 3    | $\gamma_M0$ | 1.1   | 1.15  | 1.2   | 1.0   |       |       |
| Cross-section 4           | $\gamma_M1$ | 1.1   | 1.15  | 1.2   | 1.0   |       |       |
| Member’s stability        | $\gamma_M2$ | 1.3   |       |       | 1.1   |       |       |
| Weak cross-sections       | $\gamma_M2$ | 1.3   |       |       |       |       |       |

The important fact is that in the transformed standard CSN EN 1993-1-1:2006, in accordance with the original European standard EN 1993-1-1:2005 significantly changed values of individual coefficients $\gamma_M$ were proposed.

The fundamental change is that in the actual standard CSN EN 1993-1-1:2006 the differentiation of $\gamma_M$ coefficients depending on the strength class of steels is not considered and that the $\gamma_M$ coefficients have smaller values than in the previous standards CSN 73 1401:1994. These changes are serious in both reliability and economic nature. They should therefore be based on up-to-date and relevant statistical data confirming the higher quality and uniformity of currently produced and recommended structural steels.

Consistently probabilistic-statistical determination of the strength of structural steels and materials requires large sets of necessary data obtained by standardized tests. This presupposes the permanent supplementation and updating of the relevant databases, in accordance with the development of the production of structural steels and the expansion of the material base for the fabrication of steel structures. Such activities are practically not provided in our country. At the same time, they should be carried out at the international level, in accordance with the promoted and applied free market provision of suitable materials that are necessary for the construction of a specific steel structure. It is therefore primarily up to the manufacturers of individual materials and structures to always ensuring their reliability at the required level according to the relevant material standards as well as the applicable standards for the design of steel structures [1, 5].

The following part of the paper presents and analyzes the values of the yield strength of the company, as well as the structural steel S235, which was used for the production of test bars for the research of welded steel structures [4, 5]. To determine the characteristic values of yield strength $f_y$ and design values of strength $f_d$ and resistance $f_{Rd}$ of the materials used, the procedures allowed by the actual European standard EN 1990: 2002 and the transformed standard CSN EN 1990: 2004 are effectively used and practically verified.

3. Evaluation of strength and resistance of structural steels

In the previous period, the author carried out comprehensive experimental programs of research into the elastic-plastic stability and bearing capacity of welded steel bars - beams and columns of materially quasi-homogeneous and combined I cross-sections. The research programs considered included a total of 119 test bars: VP1: 32, VP2: 55 and VP3: 32 [4, 5]. All test bars were produced in the level bridge-production plants under normal production and technological conditions. Prior to the tests themselves, their actual geometric dimensions and material properties were examined in detail. The geometric dimensions of the cross-sections - height $h$, width $b$, and flange thickness $t_f$ and web thickness $t_w$ were measured at both ends and in the middle of the bars. The corresponding average values were then considered to be their actual cross-sectional dimensions.
Material characteristics - yield strength $f_y$, tensile strength $f_u$, elongation $A_5$, as well as modulus of elasticity $E$ and modulus of reinforcement $E_0$ were determined by tensile tests of standardized specimens specially made of flanges and webs of test bars. Seven test specimens were made and tested from each bar, 2 from both flanges and 3 from the web. The corresponding average values were then considered to be the actual material characteristics of the flanges and webs of the individual bars. The actual cross-sectional dimensions and material characteristics were then used to evaluate and analyze the experimental results obtained.

A total of 5 types of Czech-Slovak steels of different strength classes (S235, S355, S440, S530 and S685) were used for the production of all test bars. In accordance with the intention in this paper, only the basic structural steel S235 (11 373.1, 11 375.1), which was used for the flanges and webs of the members of the research program VP1 and for the webs of all members of the programs VP2 and VP3, is evaluated [4, 5]. According to the considered standards CSN 731401: 1994 and CSN EN 1993-1-1: 2006, the nominal and characteristic value of S235 steel is $f_y = 235$ MPa. Partial material factor for this type of steel is $\gamma_M = 1,1$, resp. $\gamma_M = 1,0$. Therefore standard design strengths according these standards $f_d = 213,64$ MPa resp. 235 MPa.

The determined yield strengths of flanges $f_{yf}$, webs $f_{yw}$ and flanges and webs $f_y$ as well as cross-sectional deviations of flanges $\phi_{Af}$, webs $\phi_{Aw}$ and cross-sections $\phi_A$ of the test bars were in detail evaluated. For illustration see Figure 1. Statistical characteristics of the relative values of cross-sectional areas of flanges $\phi_{Af}$, webs $\phi_{Aw}$ and cross-sections $\phi_A$ of test bars made of steel S235 (research programs VP1, VP2 and VP3) are presented in Table 2.

![Figure 1. Histograms of the yield strength $f_{yw}$, $f_y$ and relative values $\phi_{Aw}$, $\phi_A$ of the cross-sections of test bars made of steel S235.](image-url)
are available and no previous knowledge and necessary statistical characteristics are available.

In the case of design resistances $f_{d}$ and resistance $f_{d,d}$ for the flanges and webs of the test bars were determined within the individual research programs and summaries. In the case of design resistances $f_{d,d}$, the determined dimensional, resp. cross-sectional deviations not taken into account in the standards considered. The determined values of $f_{y}$, $f_{d}$ and $f_{d,d}$ are summarized in the following Table 3 (assumed logarithmic-normal distribution of occurrence).

Using the relevant statistical characteristics and applying the corresponding standard relationships, the characteristic values of yield strength $f_{y}$ and design strength $f_{d}$ and resistance $f_{d,d}$ for the flanges and webs of the test bars were determined within the individual research programs and summaries. In the case of design resistances $f_{d,d}$, the determined dimensional, resp. cross-sectional deviations not taken into account in the standards considered. The determined values of $f_{y}$, $f_{d}$ and $f_{d,d}$ are summarized in the following Table 3 (assumed logarithmic-normal distribution of occurrence).

The considered standards EN 1990: 2002 and CSN EN 1990: 2004 for determining the characteristic and design strength values of structural steels by means of tests consider, depending on the existing results and knowledge, the following two cases a, b.

### Table 2. Statistical characteristics of the relative values of cross-sectional areas of flanges $\varphi_{a_{f}}$, webs $\varphi_{a_{w}}$ and cross-sections $\varphi_{a}$ of test bars made of steel S235.

| Program | VP1 | VP2 | VP3 | VP1+VP2+VP3 |
|---------|-----|-----|-----|-------------|
| $n_a$   | 32  | 32  | 32  | 55          |
| $m_a$   | 1.0207 | 1.0538 | 1.0344 | 1.0343 | 1.0481 | 1.0433 | 1.0433 |
| $s_a$   | 0.0160 | 0.0421 | 0.0228 | 0.0488 | 0.0347 | 0.0441 | 0.0441 |
| $\gamma_a$ | 0.0157 | 0.0400 | 0.0220 | 0.0472 | 0.0331 | 0.0423 | 0.0423 |
| $a_{\varphi}$ | 0.5450 | 1.1708 | 0.6367 | 0.6133 | -0.4612 | 0.4542 | 0.4542 |
| $\varphi_{a_{\min}}$ | 0.9925 | 0.9929 | 0.9948 | 0.9415 | 0.9886 | 0.9414 | 0.9414 |
| $\varphi_{a_{\max}}$ | 1.0595 | 1.1791 | 1.0808 | 1.1700 | 1.0898 | 1.1791 | 1.1791 |
| $\Delta \varphi_a$ | 0.0670 | 0.1862 | 0.0859 | 0.2285 | 0.1012 | 0.2376 | 0.2376 |

The individual statistical quantities in the Table 2 mean: $n_a$ - number, $m_a$ - average value, $s_a$ - standard deviation, $\gamma_a$ - coefficient of variation, $a_{\varphi}$ - slant, $\varphi_{a_{\min}}$ - minimum value, $\varphi_{a_{\max}}$ - maximum value, $\Delta \varphi_a$ - difference of extreme values.

### Table 3. Characteristic and design values of strength and resistance of structural steel S235.

| Strength/resistance | VP1 | VP2 | VP3 | VP1+VP2+VP3 |
|---------------------|-----|-----|-----|-------------|
| $f_{y}$             | a   | 205.840 | 206.618 | 205.840 |
|                     | b   | 206.618 | 206.618 | 206.618 |
| $f_{y_{w}}$         | a   | 228.781 | 290.748 | 293.425 | 265.852 |
|                     | b   | 230.564 | 291.558 | 294.188 | 266.290 |
| $f_{y}$             | a   | 198.272 | 230.415 | 230.853 | 230.853 |
|                     | b   | 199.181 | 230.853 | 230.853 | 230.853 |
| $f_{d}$             | a   | 183.743 | 183.743 | 183.743 | 183.743 |
|                     | b   | 187.358 | 187.358 | 187.358 | 187.358 |
| $f_{d_{w}}$         | a   | 181.098 | 253.971 | 271.351 | 225.414 |
|                     | b   | 188.509 | 257.646 | 275.017 | 227.340 |
| $f_{d}$             | a   | 153.550 | 183.396 | 183.184 | 183.184 |
|                     | b   | 157.221 | 183.184 | 183.184 | 183.184 |
| $f_{d_{d,t}}$       | a   | 186.380 | 186.380 | 190.148 | 190.148 |
|                     | b   | 190.148 | 190.148 | 190.148 | 190.148 |
| $f_{d_{d,w}}$       | a   | 187.188 | 229.318 | 229.318 | 229.318 |
|                     | b   | 195.169 | 231.421 | 231.421 | 231.421 |
| $f_{d_{d}}$         | a   | 158.073 | 185.548 | 185.548 | 185.548 |
|                     | b   | 161.888 | 187.432 | 187.432 | 187.432 |

a) available only the results of small number selection tests n
b) previous knowledge providing a priori results is also available in addition to the results of sample tests

The first case (a) is general and unambiguous if only the results of a limited number of n sample tests are available and no previous knowledge and necessary statistical characteristics are available (mean
value \( \mu_y \), standard deviation \( \sigma_y \) and coefficient of variation \( \nu_y \). In EN 1990: 2002 and CSN EN 1990: 2004, it is recommended to consider the second case (b) with a conservative estimate of the coefficient of variation \( \nu_y \).

However, in the context of the above remarks on the nature and relationship of previous statistics to the new set of material test results to be used for a particular design, any estimate of the coefficient of variation \( \nu_y \) seems problematic. With thorough and sufficient verification of all materials used for a particular construction, the corresponding coefficient of variation \( \nu_y \) should probably be considered representative and known. If the first method (a) is used, then the coefficient of variation \( \nu_y \) should not be considered to be less than 0.1 according to these standards. With regard to the number of tests, it is based on the assumption of a normal - symmetrical distribution or a two-parameter logarithmic-normal distribution of the occurrence of the evaluated strength. The corresponding inclination \( \alpha_y \) is not considered, but it can be very significant.

The obtained and partial presented histograms and statistical characteristics, as well as the calculated characteristic and design values of strength and resistance of the evaluated structural steels and materials of the considered test bars allow discussion and evaluation of the results from several relevant perspectives.

4. Conclusions
The examined values of yield strength \( f_{yf,i} \) and \( f_{yw,i} \) can be responsibly considered in accordance with [4, 5] when assessing the load-bearing capacity of individual test bars. For test bars of individual research programs, reliably consider also the minimum values of the determined yield strength \( f_{yf,\text{min}} \) and \( f_{yw,\text{min}} \). These values are close to or higher, up to significantly higher than the corresponding standard design strength value \( f_{yf,\text{CSN}} \).

The test bars were produced in two stages with a time lag at two manufacturers, the values found for the yield strength of flanges and webs \( f_{yf} \) and \( f_{yw} \) are probably relatively different, however, the effect of thicknesses and rolling of the materials used is also evident. The yield strength of \( f_{yf} \) flanges is generally smaller than the yield strength of \( f_{yw} \) webs. However, even the minimum value of \( f_{yf,\text{min}} \) is practically equal to the design value of strength \( f_{yf,\text{CSN}} \) determined with the coefficient \( \gamma_{Mb} = 1.1 \). Certain differences were also found in the proposed and actual cross-sectional areas of flanges and webs of test bars of the individual research programs, they are characterized by the detected deviations \( \phi_a \). Due to their size (\( \phi_{a,\text{min}} = 0.9414 \) and \( \phi_{a,\text{max}} = 1.1791 \)), the test members considered were also taken into account when determining the design values of the material resistance \( f_{Rd} \).

From the point of view of the paper and the adequacy of determining the characteristic and design values of strength and resistance of structural materials based on test results, it is important to compare the determined characteristic value of yield strength \( f_y \) with the design strength \( f_d \) and resistance \( f_{Rd} \) - Table 3.

Determination and verification of strength characteristics of structural steels and materials on the basis of relevant test results and presented procedures according to the actual standards is justified and necessary especially for generally demanding structures. The results of the presented evaluation encourage caution in the application of partial reliability coefficients of structural steels and materials according to the actual standards for the design of steel structures.

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