Strength Verification of Structural Steels and Materials

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Abstract. There is already a relatively wide range of structural steels and materials of various shapes and strengths for manufacturing of steel structures. They produce in different countries of Europe and the world. It is primarily a matter of the manufacturer, resp. the contractor of the steel structure with the vat and under what conditions he will provide the necessary construction materials. In addition to the price point of view, the quality of the considered construction materials is probably important. In particular, their geometric and strength suitability and accuracy are taken into account here. The quality of structural steels and materials is generally specified in the relevant standards and is the responsibility of the respective manufacturers. They declare it in the so-called quality certificates. At the same time, for various reasons, there may be a need to verify the declared quality, in particular the strength of specific structural steels and materials. The paper presents common probabilistic-statistical procedure and the strength procedures of structural steels and materials based on the test results, which are enabled by the current European standard EN 1990: 2002 as well as the transformed national standard CSN EN 1990: 2004, and similar other national standards. The practical application of the individual procedures and some details are illustrated by a specific example.

1. Introduction

Current standards for the design of steel structures contain a number of recommended structural steels of various strengths. These standards also state the basic strength characteristics of individual structural steels. These are mainly the yield strength $f_y$, resp. $R_y$, tensile strength $f_u$, resp. $R_m$ and ductility $A_d$. The yield strengths and tensile strengths of the recommended structural steels depend on a number of random variables. For practical purposes, however, they are determined and standardized by specific 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 [1-4].

Consistent probabilistic-statistical determination of the strength characteristics of structural steels requires large sets of the necessary data obtained by standardized tests. It should be noted that the probabilistic-statistically determined strength values of structural steels and materials are always only hypothetical, as they are determined on the basis of previous tests of already produced steels and materials for the design and construction of future structures. The determination of the strength of structural steels and materials by means of tests is enabled by the current European standard EN 1990: 2002 and transformed national standards, in CR it is CSN EN 1990: 2004. Effective determination of
the strength of structural steels and materials is also enabled by simulation methods in which many new statistical sets of randomly variable strength quantities are created according to the chosen mathematically formulated type of probability distribution and their available information and statistical data obtained by tests. The Monte Carlo method is considered to be a very suitable simulation method for such purposes [5]. This paper provides basic information on determining the strength characteristics of structural steels and materials according to the indicated procedures and the relevance of statistical data. At the same time, these procedures are applied and compared in the evaluation of strength properties of selected structural steels S355 ML and S420 ML, which were used for the bridge Apollo in Bratislava [6].

2. Procedures for determining the strength of structural steels

Probabilistic-statistical procedure

Strength of structural steel expressed in general functional form

\[ f(x) = f(x_1, x_2, x_3, \ldots, x_n) = ([x]_1, [x]_2, [x]_3, \ldots, [x]_k), \quad n = \sum_{i=1}^{k} n_i, \]  

where \( x_1, x_2, x_3 \) to \( x_n \), resp. \([x]_1, [x]_2, [x]_3\) to \([x]_k\) are individual random variables whose frequencies are \( n_1, n_2, n_3 \) to \( n_k \), \( n \) is the number of all random variables of steel strength \( f_i \) determined by tests.

In general, for structural steels, tensile tests determine the yield strength \( f_y \) and the tensile strength \( f_u \). For normative purposes and for the purposes of practical design, their characteristic values (determined with a probability of failure \( P_f = 0.05 \)) and design values (determined with a probability of failure \( P_d = 0.001 \)) are important. The characteristic values of the yield strength \( f_y \) and the tensile strength \( f_u \) of the structural steel are determined by the relations:

\[ f_y = m_{fy} - \beta_{f,y,a} s_{fy} = m_{fy} (1 - \beta_{f,y,a} \nu_{fy}) \]  

(2a)

\[ f_u = m_{fu} - \beta_{f,u,a} s_{fu} = m_{fu} (1 - \beta_{f,u,a} \nu_{fu}) \]  

(2b)

The design strength values of structural steel shall be determined using the relationships:

\[ f_{yd} = m_{fy} - \beta_{f,y,d,a} s_{fy} = m_{fy} (1 - \beta_{f,y,d,a} \nu_{fy}) \]  

(3a)

\[ f_{ud} = m_{fu} - \beta_{f,u,d,a} s_{fu} = m_{fu} (1 - \beta_{f,u,d,a} \nu_{fu}) \]  

(3b)

where \( m_f \) is the mean value, \( s_f \) is the standard deviation and \( \nu_f \) is the coefficient of variation of the relevant set of strength values \( f_s \), \( \alpha_f \) is asymmetry coefficient or slant [1,2].

Standard procedures

Depending on the relevance of the test results, the actual standards EN 1990: 2002, CSN EN 1990: 2004 and other assume the following two cases:

a) Only the results of a small number \( n \) of sample tests are available.

b) In addition to the results of the selection tests, previous knowledge providing a priori results is also available.

The first case is general and unambiguous - a, if only results from a limited number of \( n \) sample tests are available and no previous knowledge of the necessary statistical characteristics (mean value \( m_f \), standard deviation \( s_f \) and coefficient of variation \( \nu_f \)) is available. In the standards it is recommended to use the second case - b, with a conservative estimate of the coefficient of variation \( \nu_f \). In both cases,
due to the number of tests, the assumption of a normal distribution or a two-parameter logarithmic-normal distribution of the occurrence of the evaluated strength is assumed. It is therefore not considered with a corresponding slant \( a_s \), which, however, can be very significant, especially in a small number of tests [1, 2].

If normal distribution of the evaluated strength is assumed the characteristic values of the yield strength \( f_y \) and the tensile strength \( f_u \) of evaluated structural steel are determined:

\[
\begin{align*}
  f_y &= m_y (1 - k_y v_y), \\
  f_u &= m_u (1 - k_y v_u)
\end{align*}
\]  

(4a, 4b)

The design strength values of the evaluated structural steel are determined:

\[
\begin{align*}
  f_{yd} &= m_y (1 - k_d v_y), \\
  f_{ud} &= m_u (1 - k_d v_u)
\end{align*}
\]  

(5a, 5b)

The values of the coefficients \( k_y \) and \( k_d \) are contained in the standards EN 1990: 2002, CSN EN 1990: 2004 and other.

In accordance with the design method according to the limit states, the ratios of the determined characteristic values of the yield strength \( f_y \) or the tensile strength \( f_u \) and the design values of the strength \( f_{yd}, f_{ud} \) actually express the partial reliability coefficients of the evaluated structural steel \( \gamma_{M0} \) and \( \gamma_{M2} \).

\[
\begin{align*}
  f_{yd} &= f_y / \gamma_{M0}, \\
  f_{ud} &= f_u / \gamma_{M2}
\end{align*}
\]  

(6a, 6b)

If the log-normal distribution of the evaluated strength is assumed the characteristic values of the yield strength \( f_y \) and the tensile strength \( f_u \) of the evaluated structural steel are determined:

\[
\begin{align*}
  f_y &= \exp(m_{y,\ln} - k_y s_{y,\ln}) \equiv m_y \exp(-k_y v_y) \\
  f_u &= \exp(m_{u,\ln} - k_y s_{u,\ln}) \equiv m_u \exp(-k_y v_u)
\end{align*}
\]  

(7a, 7b)

The design strength values of the evaluated structural steel are determined:

\[
\begin{align*}
  f_{yd} &= \exp(m_{y,\ln} - k_d s_{y,\ln}) \equiv m_y \exp(-k_d v_y) \\
  f_{ud} &= \exp(m_{u,\ln} - k_d s_{u,\ln}) \equiv m_u \exp(-k_d v_u)
\end{align*}
\]  

(8a, 8b)

The values of the coefficients \( k_y \) and \( k_d \) are contained in the standards EN 1990: 2002, CSN EN 1990: 2004 and other.

3. Strength evaluation of selected structural steels

The yield strength \( f_y \) and the tensile strength \( f_u \) of sheets with thickness \( t \leq 40 \text{ mm} \) made of structural steels S355 ML and S420 ML are evaluated on the basis of a database of certificate results [5, 6]. The relevant standard characteristic and design strengths of the evaluated structural steels are:

Steel S355 ML → \( f_y = 355.00 \text{ MPa}, f_{yd,EN} = 355.00 \text{ MPa}, f_{u,EN} = 295.83 \text{ MPa}, \)
\( f_{u,EN} = 470.00 \text{ MPa}, f_{u,EN} = 427.27 \text{ MPa}, f_{u,EN} = 361.54 \text{ MPa}. \)

Steel S420 ML → \( f_y = 420.00 \text{ MPa}, f_{yd,EN} = 420.00 \text{ MPa}, f_{u,EN} = 336.00 \text{ MPa}, \)
\( f_{u,EN} = 520.00 \text{ MPa}, f_{u,EN} = 472.73 \text{ MPa}, f_{u,EN} = 400.00 \text{ MPa}. \)
The considered sets of $f_y$ and $f_u$ are contained in Table 1. The corresponding histograms are shown in Figure 1. The results of the statistical evaluation of the considered structural steels are in Table 2.

Table 1. Sets of the yield strength $f_y$ and tensile strength $f_u$.

| Steel S355 ML | Steel S420 ML |
|---------------|---------------|
| $f_y$ | $f_u$ | $f_y$ | $f_u$ |
| Classes | Count | Classes | Count | Classes | Count | Classes | Count |
| 360 | 0 | 460 | 0 | 360 | 0 | 460 | 0 |
| 370 | 0 | 470 | 0 | 370 | 0 | 470 | 0 |
| 380 | 1 | 480 | 5 | 380 | 0 | 480 | 0 |
| 390 | 6 | 490 | 7 | 390 | 0 | 490 | 0 |
| 400 | 7 | 500 | 37 | 400 | 0 | 500 | 2 |
| 410 | 11 | 510 | 24 | 410 | 10 | 510 | 0 |
| 420 | 23 | 520 | 34 | 420 | 10 | 520 | 15 |
| 430 | 24 | 530 | 28 | 430 | 18 | 530 | 14 |
| 440 | 22 | 540 | 16 | 440 | 19 | 540 | 21 |
| 450 | 24 | 550 | 13 | 450 | 20 | 550 | 18 |
| 460 | 18 | 560 | 8 | 460 | 15 | 560 | 27 |
| 470 | 16 | 570 | 1 | 470 | 15 | 570 | 22 |
| 480 | 12 | 580 | 2 | 480 | 7 | 580 | 17 |
| 490 | 6 | 590 | 1 | 490 | 3 | 590 | 3 |
| 500 | 3 | 600 | 0 | 500 | 12 | 600 | 2 |
| 510 | 1 | 610 | 0 | 510 | 8 | 610 | 0 |
| 520 | 0 | 620 | 0 | 520 | 2 | 620 | 2 |
| 530 | 0 | 630 | 0 | 530 | 1 | 630 | 0 |
| 540 | 2 | 640 | 0 | 540 | 2 | 640 | 0 |
| 550 | 0 | 650 | 0 | 550 | 1 | 650 | 0 |
| 560 | 0 | 660 | 0 | 560 | 1 | 660 | 1 |

Total number of values $n = 176$  
Total number of values $n = 144$

Table 2. Results of statistical evaluation of the steel S355 ML and S420 ML.

| Parameter | S355 ML | S420 ML |
|-----------|---------|---------|
| Number of values $n$ | 176 | 176 | 144 | 144 |
| Average value $m$ | 439.13 | 516.31 | 454.35 | 549.49 |
| Average value $m_{ln}$ | 6.0828 | 6.2459 | 6.1163 | 6.3081 |
| Standard deviation $s$ | 27.997 | 20.879 | 32.741 | 23.566 |
| Standard deviation $s_{ln,a}$ | 0.0632 | 0.0401 | 0.0708 | 0.0424 |
| Standard deviation $s_{ln,b}$ | 0.0637 | 0.0404 | 0.0720 | 0.0429 |
| Coefficient of variation $v$ | 0.0638 | 0.0404 | 0.0721 | 0.0429 |
| Slant $a$ | 0.4334 | 0.5070 | 0.6707 | 0.6660 |
| Minimum value $f_{min}$ | 379 | 474 | 401 | 498 |
| Maximum value $f_{max}$ | 539 | 582 | 556 | 652 |
| Difference of extreme values $\Delta f$ | 160 | 108 | 155 | 154 |
For both structural steels, characteristic and design values of strength $f_y$, $f_u$, $f_{yd}$ and $f_{ud}$ are determined according to the presented probabilistic statistical procedure (PP) and according to the standard procedure (NP). In the case of a probabilistic-statistical procedure, a normal distribution, a log-normal distribution and a gamma distribution of the evaluated strengths are assumed [1, 2]. The standard procedure assumes a normal and log-normal distribution of the evaluated strengths, a small number of $n$ sampling tests is considered (case a). For comparison, the values of strengths $f_y$, $f_u$, $f_{yd}$ and $f_{ud}$ are also determined by the simulation method Monte Carlo (MC) using the calculation program MC-SIMUL [7]. The determined characteristic values $f_y$, $f_u$ and design values $f_{yd}$, $f_{ud}$, as well as their mutual comparison are summarized in Table 3 and 4.

Table 3. Characteristic and design values of strength and their mutual comparison, S355 ML.

| Procedure and expected distribution | $f_y$ (MPa) | $f_u$ (MPa) | $f_{yd}$ (MPa) | $f_{ud}$ (MPa) | $f_y/f_{yd}$ | $f_u/f_{ud}$ |
|------------------------------------|-------------|-------------|----------------|----------------|---------------|---------------|
| PP                                 | 392.90      | 482.10      | 352.56         | 451.86         | 1.114         | 1.067         |
| normal                             | 396.66      | 485.14      | 367.38         | 464.76         | 1.080         | 1.044         |
| gama                               | 396.86      | 485.32      | 369.26         | 466.40         | 1.075         | 1.041         |
| normal                             | 392.76      | 481.75      | 350.92         | 450.55         | 1.119         | 1.069         |
| NP                                 | 394.70      | 482.75      | 359.12         | 454.67         | 1.099         | 1.062         |
| log.-normal                        | 399.78      | 486.76      | 355.08         | 458.25         | 1.126         | 1.062         |
| MC                                 | 390.34      | 483.77      | 356.62         | 455.50         | 1.095         | 1.062         |
4. Discussion

In the presented evaluation, the current procedures for determining the characteristic and design strength values of the considered structural steels were applied. The obtained results do not show more significant differences between the individual procedures and the expected distributions of the random occurrence due to relatively homogeneous sets of the evaluated values of yield strength \( f_y \) and tensile strength \( f_u \). The obtained results also provide essential information about the basic strength properties of the assessed structural steels. They result in certain qualitative differences.

The determined characteristic and design strength values of structural steel S355 ML comply with the relevant standard values, resp. they even exceed them. In this context, when determining the design values of strength \( f_{ud} \) and \( f_{ud} \), it is also possible to accept the values of partial reliability coefficients of the assessed steel \( \gamma_{M0} = 1.0 \) and \( \gamma_{M2} = 1.1 \) according to the actual standards for design of steel structures EN 1992-1-1: 2005 and CSN EN 1993-1-1: 2007. The coefficients \( \gamma_{M0} = 1.2 \) and \( \gamma_{M2} = 1.3 \) according to the previous standard CSN 73 1401: 1994 appear to be too safe for the evaluated structural steel.

The determined characteristic values of the yield strength \( f_y \) of the structural steel S420 ML are less than or close to the standard value \( f_{y,N} \). The corresponding differences are insignificant. However, the determined design values \( f_{ud} \) are significantly smaller than the standard value \( f_{ud,EN} \). Based on these results, it can be stated that the partial reliability factor \( \gamma_{M0} = 1.0 \) according to the actual standards EN 1992-1-1: 2005 and CSN EN 1993-1-1: 2007 is not safe. The achieved result is better satisfied by the partial coefficient \( \gamma_{M0} = 1.10 \) to 1.15.

The determined characteristic values of the tensile strength \( f_u \) of the structural steel S420 ML are close to the standard value \( f_{u,N} \). The achieved result is satisfied by the partial reliability factor \( \gamma_{M2} = 1.1 \) according to the actual standards for the design of steel structures EN 1992-1-1: 2005 and CSN EN 1993-1-1: 2007. The coefficient \( \gamma_{M2} = 1.3 \) according to the previous standard CSN 73 1401: 1994 appear to be too safe for the evaluated structural steel.

5. Conclusion

Determination and verification of strength characteristics of structural steels and materials on the basis of relevant test results and presented procedures according to actual standards is justified and necessary especially for generally demanding structures.

The results of the evaluation of the strength properties of the assessed structural steels S355ML and S420ML show certain qualitative differences. In this context, the uniform values of partial reliability coefficients \( \gamma_{M0} \) and \( \gamma_{M2} \) (\( \gamma_{M0} = 1.0 \) and \( \gamma_{M2} = 1.1 \)) promoted for all structural steels of different strengths appear to be unjustified.

### Table 4. Characteristic and design values of strength and their mutual comparison, S420 ML.

| Procedure and expected distribution | \( f_y \) | \( f_u \) | \( f_{ud} \) | \( f_{ud} \) | \( f_y / f_{ud} \) | \( f_u / f_{ud} \) |
|------------------------------------|---------|---------|---------|---------|----------------|----------------|
| PP                                 | 400.46  | 510.71  | 353.12  | 476.65  | 1.134          | 1.071          |
| normal                             |         |         |         |         |                |                |
| log.-normal                        | 406.86  | 515.39  | 379.94  | 495.81  | 1.071          | 1.039          |
| gama                               | 407.37  | 515.64  | 383.33  | 498.24  | 1.063          | 1.035          |
| normal                             | 400.04  | 510.40  | 350.79  | 474.96  | 1.140          | 1.075          |
| NP                                 | 403.02  | 511.69  | 362.33  | 480.05  | 1.112          | 1.066          |
| log.-normal                        |         |         |         |         |                |                |
| normal                             | 417.74  | 520.39  | 373.89  | 478.71  | 1.117          | 1.087          |
| MC                                 | 408.95  | 513.47  | 372.79  | 482.08  | 1.097          | 1.065          |
| log.-normal                        |         |         |         |         |                |                |
The results of the presented evaluation encourage caution in the application of partial reliability coefficients of structural steels and materials according to actual standards for the design of steel structures.

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