Influence of Steel Yield Strength Value on Structural Reliability

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Abstract: - The paper is generally focused on the problems of the yield strength and ultimate strength of structural steels. The attention is mainly paid to the determination of the characteristic (respectively nominal) and design values of steel strengths, especially from the viewpoint of the rules given in European Standards (EN) and from this arising problems of the failure probability and reliability of steel structures. The paper deals with the actual yield strength obtained from the material tests and its actual characteristic and design values determined based on the tests versus nominal and design values considered according to EN rules. The statistical differences between actual and standard values are shown in this paper.

Key-Words: - Structural steel, material test, yield strength, ultimate strength, characteristic value, design value, nominal value, statistic, failure probability, reliability, limit state function, Monte Carlo simulation.

1 Introduction

According to European Standards (see e.g. [1], [2]), structural material properties and other parameters, especially strengths are given by characteristic and design values in the case of the most materials. The characteristic strength is statistically defined (with only some exceptions) as 5 % fractile and the design value as 0.01 % fractile, with respect to the required resulting structural reliability which is derived from the allowable failure probability. This principle is usually used in the case of concrete, timber, steel reinforcement, for example, and so on. But for yield strength of structural steels used for load-carrying structures of civil engineering constructions the nominal value instead of characteristic value is used mostly.

2 Problem Formulation

In usual cases the design value of material property X_d is calculated according to the formula

$$X_d = \frac{X_k}{\gamma_M}, \quad (1)$$

where X_k is the characteristic value of the property and γ_M is the partial safety factor for material and as a rule $\gamma_M \geq 1$. But the design value of steel yield strength f_{yd} is in the most cases given as

$$f_{yd} = \frac{f_y}{\gamma_M}, \quad (2)$$

where f_y is not the characteristic yield strength, but its nominal value, and partial safety factor $\gamma_M = 1$. It is caused just by the utilized value of f_y, which does not correspond to 5 % fractile, but it is larger than one. It follows from the fact, that the producers of steel structural members give in their catalogues and tables the strength values differently evaluated and determined, so they are not the characteristic values.

So far many specialists discussed and criticized this problem (see [Mrázik], for example), especially from the viewpoints of the (in)sufficient reliability, or on the contrary, the (un)economy.

2.1 Tensile Testing

The actual value of the yield strength is determined using the tensile diagram of steel obtained from the tensile testing.

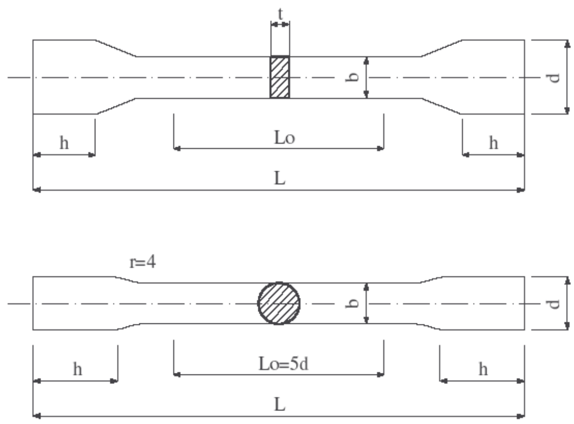

Fig. 1 Standard specimens for steel properties tests

Test specimens, testing process and methods of the test results evaluation for the tensile testing are prescribed in EN ISO 6892-1 [3]. The typical shape and dimensions of the test specimen are shown in Fig. 1, but in some special cases (sampling from real structure, for example, if no-adequate dimensions of the member are available) the test specimens can be modified.

The direct result of tensile testing is stress "σ – strain ε" diagram (see Fig. 2), from which the actual values of basic material parameters (yield strength, ultimate strengths, Young's modulus of elasticity) are determined as known generally. The basic points of this diagram, which characterize steel behaviour in tension, are shown from Fig. 2, too. Subsequent elaboration is oriented to the statistical evaluation of the yield and ultimate strength.

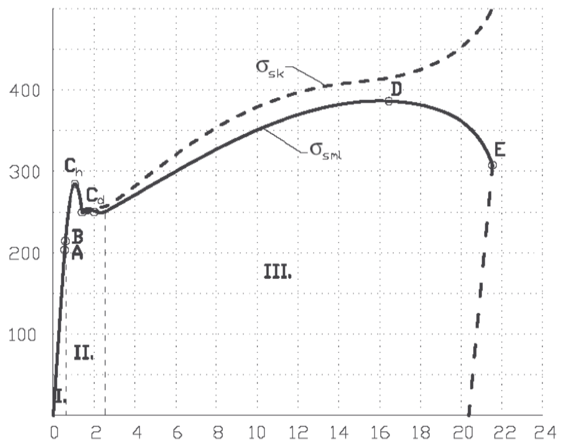

Fig. 2 Typical "$\sigma - \varepsilon$" (stress – strain) diagram of steel with significant yield strength

2.2 Material Property Statistical Evaluation

As mentioned above, values of steel yield strength given in producers backgrounds do not correspond with the characteristic value. The characteristic and design values of material property can be obtained from the tests using methods of the design assisted by testing described in the European Standard EN 1990 [1]. These methods consistently respect the test number and also the property distribution type.

Characteristic values X_k and design values X_d of the material property can be given by the formulas:

$$X_k = m_X \cdot (1 - k_n \cdot v_X) \tag{1}$$

$$X_d = m_X \cdot (1 - k_{d,n} \cdot v_X) \tag{2}$$

in the case of normal distribution of the property, or

$$X_k = \exp(m_{\ln X} - k_n \cdot s_{\ln X}) \cong m_X \cdot \exp(-k_n \cdot v_X) \tag{3}$$

$$X_d = \exp(m_{\ln X} - k_{d,n} \cdot s_{\ln X}) \cong m_X \cdot \exp(-k_{d,n} \cdot v_X) \tag{4}$$

in the case of log-normal property distribution.

The fractile factors k_n and $k_{d,n}$ are determined in dependence on the test number and on the variation coefficient v_X, which can be "known" from previous experiences, or "unknown", that means determined from the test data (for more and details see [1]).

3 Experimental Determination of Steel Yield Strength

Within the framework of experimental verification of various types of steel and steel-concrete structural members, also material tests have been performed, to obtain the actual values of material properties for subsequent elaboration and evaluation of test results and for the verification of numerical models.

On the following examples the actual steel yield strengths obtained from the material tests, as well as the evaluation and derivation of characteristic and design yield strengths is shown. For these examples the material test results of hot-rolled members with I and HEA cross-sections and steel grades S 235 and S 355 have been utilized. In Fig. 3 the illustration of standard specimens is seen.

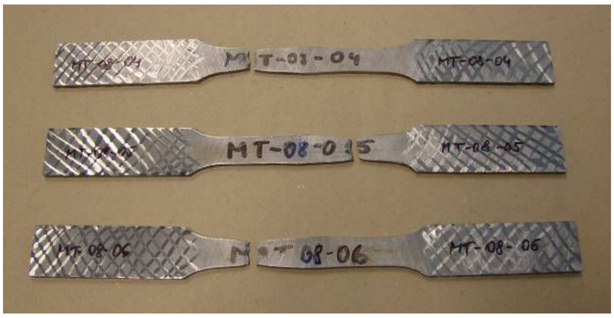

Fig. 3 Illustration of standard specimens for the tests of steel mechanical properties

3.1 Steel Grade S 235

In common 26 specimens with declared steel grade of S 235 have been tested. The specimens have been taken from the members of the cross-sections I 120, I 140, I 180, I 200 and I 220.

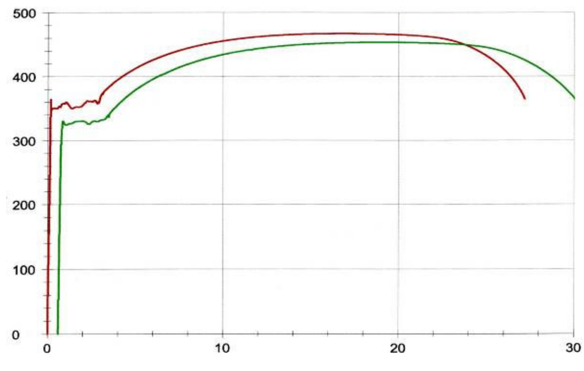

Fig. 4 Illustration of "$\sigma - \varepsilon$" diagram of steel S 235

The illustration of the typical “$\sigma - \varepsilon$” diagram of steel grade S 235 in tension is shown in Fig. 4. The statistical distribution of steel yield strength values obtained from the tests is expressed helping the histogram in Fig. 5.

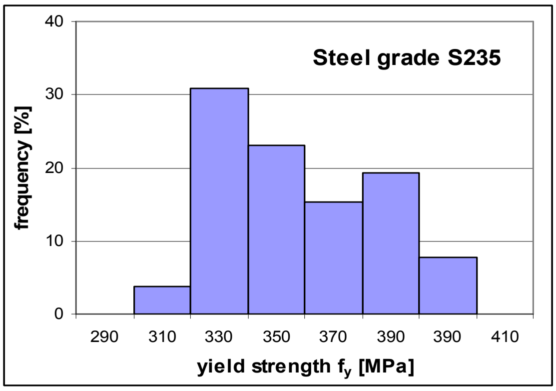

Fig. 5 Histogram of the yield strength distribution for steel grade of S 235

The overview of representative values of yield strength obtained from the material tests is shown in Table 1. In this table values for “unknown” and also for “known” variation coefficient are calculated.

Table 1 Steel yield strength obtained from the tests: steel grade S 235 – 26 tests, lognormal distribution

nominal value f_y = 235 MPa	variation coefficient v_f	
mean value f_{ym} = 327.5 MPa	$v_{f,unknown}$ 0.086	$v_{f,known}$ 0.075
characteristic value f_{yk} [MPa]	282.2	288.9
design value f_{yd} [MPa]	242.4	258.8

Because the “unknown” variation coefficient can be unfavourably (here, variation coefficient is more than usual values) influenced by the test number and random of the occurrence of different values, for the potential generalization it is recommended to use the “known” variation coefficient. So that, particular conclusions (see below) have been derived from the values calculated using the “known” coefficient, i.e. in this case the characteristic value of yield strength is f_{yk} = 288.9 MPa and the design value of the yield strength is f_{yd} = 258.8 MPa. Thus, from Table 1 it is evident, that the actual characteristic yield strength is about by 22.9 % more and design yield strength is about by 10.1 % more than nominal yield strength, which is used instead of the characteristic value and, considering the partial safety factor γ_M = 1, also as the design yield strength.

3.2 Steel Grade S 355

In common 19 specimens with declared steel grade of S 355 have been tested including test results evaluating. Specimens have been taken from the members of HE 140A and HE 160A cross-sections.

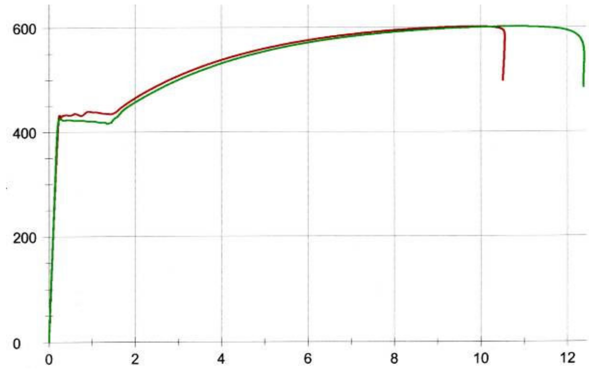

Fig. 6 Illustration of “$\sigma - \varepsilon$” diagram of steel S 355

The illustration of the typical “$\sigma - \varepsilon$” diagram of steel grade S 355 in tension is shown in Fig. 6. The statistical distribution of the yield strength values is expressed by the histogram in Fig. 7.

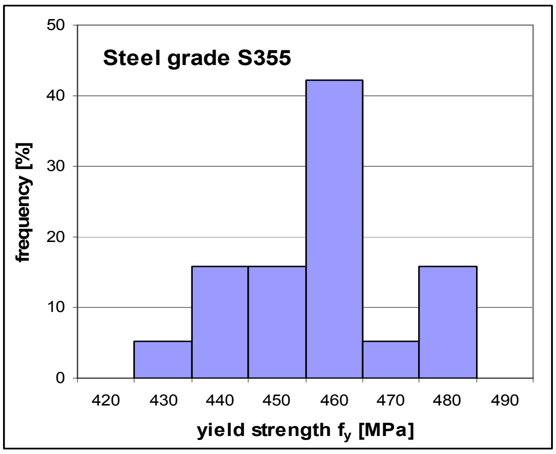

Fig. 7 Histogram of the yield strength distribution for steel grade of S 355

The overview of representative values of yield strength obtained from the material tests is shown in Table 2. Also in Table 2 the values calculated both for the “unknown” variation coefficient and for the “known” one are written.

In this case the “unknown” variation coefficient for yield strength is less than its usual values. So here, the characteristic and design yield strengths have been derived using the “known” coefficient, that means the characteristic value of yield strength is f_{yk} = 415.7 MPa and the design value of the yield strength is f_{yd} = 385.9 MPa. Hence, the characteristic value of the yield strength is about by 17.1 % more and the design yield strength is about by 8.7 % more than the nominal yield strength.

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Table 2 Steel yield strength obtained from the tests: steel grade S 355 – 19 tests, lognormal distribution

nominal value f_y = 355 MPa	variation coefficient v_f	
mean value f_{ym} = 452.2 MPa	$v_{f,unknown}$ 0.028	$v_{f,known}$ 0.05
characteristic value f_{yk} [MPa]	430.4	415.7
design value f_{yd} [MPa]	407.7	385.9

4 Steel Structural Member Reliability

The reliability of steel structure or steel structural member, respectively, can be defined using the failure probability, which is given by the limit state function according to the relevant structural member loading. The failure probability value can be also characterized by the reliability index. For "normal" reliability level of the most of civil structures the basic value of the reliability index is prescribed as β = 3.8, which corresponds to the failure probability value of about $7 \cdot 10^{-5}$. Understandably, the failure probability depends on the effect of loading actions (including all the statistical variability) on one side and on the resistance given by mechanical and geometrical properties (including all the statistical variability) on the other side. The influence of steel yield strength real statistical parameters on the resistance and subsequently on the limit state function is tried to show on the example of steel member in tension.

The design resistance of steel structural member subjected to tension is given as $N_{Rd} = A \cdot f_{yd}$. Thus the limit state function G derived from the reliability condition in the form of $N_{Ed} \leq N_{Rd}$ is represented by the format of $G_N = N_{Rd} - N_{Ed} = A \cdot f_{yd} - N_{Ed}$, where A is cross-section area, f_{yd} is the design yield strength and N_{Ed} is the design tensile force.

To calculate the failure probability and structural member reliability, respectively, the tensile member limit state function (as described above) has been determined by the statistical simulation using Monte Carlo method. For the simulation the distribution type and statistical parameters of the basic variables have been considered to be determined the influence of the yield strength only on the design resistance. Hence, the deterministic distributions of the cross-section area and log-normal distribution of the yield strength have been considered. The design tensile force has been also considered deterministically distributed, but during the simulation this one has being changed so long as the failure probability reached the value of $7 \cdot 10^{-5}$, which is competent to the reliability index of 3.8.

4.1 Design Resistance of Steel Grade S 235 Tensile Member

For the simulation of the limit state function of the tensile members composed of S 235 steel, member properties with corresponding statistical parameters according to Table 1 have been used, that means the mean value and variation coefficient of the yield strength. The limit state function parameters have been considered as shown in Table 3.

Table 3 Statistical parameters of member properties

variable	distribution	mean value	standard deviation
A [mm^2]	deterministic	2 000	---
f_y [MPa]	lognormal	327.5	24.56

The tensile force design value determined by Monte Carlo simulation using the actual yield strength and corresponding to the reliability index of 3.8 has been derived as N_{Ed} = 491.5 kN. The limit state function mean value is G_N = 163.5 kN. The illustration of the limit state function distribution obtained by MC simulation is seen in Fig. 8.

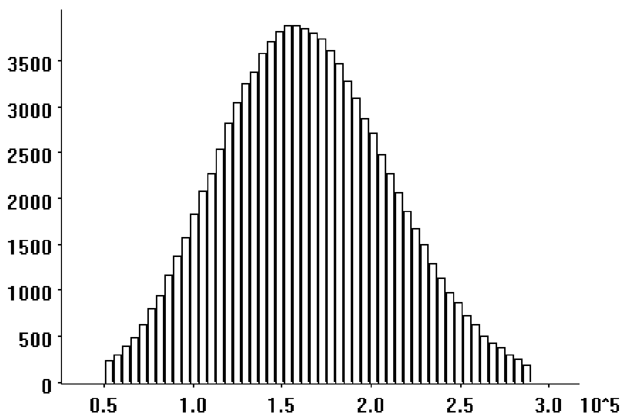

Fig. 8 Histogram of the distribution of limit state function G_N for steel grade S 235: $G_{N,m}$ = 163.5 kN

From the calculations described above it follows, the design resistance determined using the actual values and distribution of the yield strength is equal to the design tensile force competent to reliability index of 3.8, that means $N_{Rd} = N_{Ed}$ = 491.5 kN. The design resistance determined using the nominal yield strength is calculated as $N_{Rd} = A \cdot f_y / \gamma_M$, where f_y = 235 MPa and γ_M = 1, that means N_{Rd} = 470 MPa.

4.2 Design Resistance of Steel Grade S 355 Tensile Member

For the simulation of the limit state function of the tensile members composed of S 355 steel, member properties with corresponding statistical parameters according to Table 2 have been used, that means the mean value and variation coefficient of the yield strength. The limit state function parameters have been considered as shown in Table 4.

Table 4 Statistical parameters of member properties

variable	distribution	mean value	standard deviation
A [mm^2]	deterministic	2 000	---
f_y [MPa]	log-normal	452.2	22.61

Using Monte Carlo simulation the tensile force design value corresponding to the reliability index of 3.8 has been derived as N_{Ed} = 747.0 kN. The limit state function mean value is G_N = 157.4 kN. The illustration of the limit state function distribution obtained by MC simulation is seen in Fig. 9.

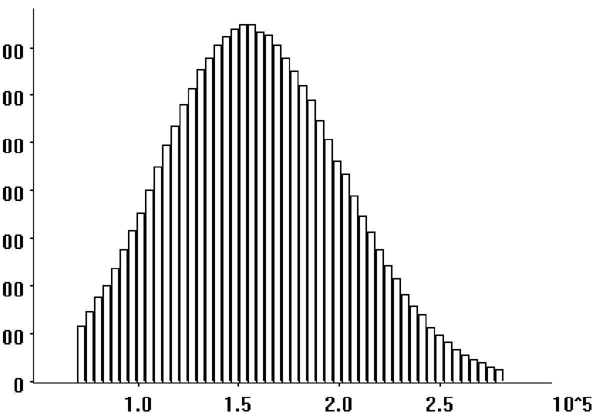

Fig. 9 Histogram of the distribution of limit state function G_N for steel grade S 355: $G_{N,m}$ = 157.4 kN

The design resistance determined using actual values and distribution of the yield strength is given as $N_{Rd} = N_{Ed}$ = 747.0 kN. The design resistance determined using the nominal yield strength is given as $N_{Rd} = A \cdot f_y / \gamma_M$, where f_y = 355 MPa and $\gamma_M = 1$, that means N_{Rd} = 710 MPa.

5 Conclusion

Based on the examples described above differences between the design resistance determined using the nominal yield strength according to the European Standards and the design resistance calculated using actual steel yield strength obtained and statistically evaluated from the tests have been shown.

For steel grade S235 the design resistance using the actual yield strength is by 4.6 % higher than the design resistance using the nominal yield strength.

For steel grade S355 the design resistance using the actual yield strength is by 5.2 % higher than the design resistance using the nominal yield strength.

It is necessary to note that the results obtained for the selected examples mentioned above can be limited to the particular member parameters, but the reached reserves can be significant, if the loading increasing is potential, in the case of reconstruction, for example.

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