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# The Use of Stainless Steel in Structures: Columns under Compression

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**Abstract.** The analysis of the limit states of load-bearing stainless steel structural members requires the inclusion of material non-linearity in the calculations of resistance and deformation. The analysis of slender columns under compression requires the inclusion of both material and geometric non-linearity, which increases demands on the numerical analysis and scientific computing. This paper focuses on some aspects of the numerical analysis of the compressive force of columns with initial imperfections, which may have a significant influence on the results of the analysis of the safety and usability of load-bearing structures with slender members. The increased accuracy of results of experimental research on the material characteristics of stainless steel is discussed in connection with the properties of carbon steel and the application of numerical analysis in stochastic computational models.

## 1. Introduction

The traditional approach to building design is based on three basic requirements: the quality of the structural design, the cost and the time required to complete the construction. However, such an approach does not take into account broader aspects in terms of the environmental impact and the social and cultural quality of the function of constructed buildings and may, in the long term, entail economic constraints at the end of the life of the buildings [1].

A specific group of structures is comprised of bridge structures, which are permanently exposed to degradation processes of the surrounding environment. The use of stainless steel as a material for load-bearing structural members of bridges is increasingly common, especially in the last twenty-five years. Stainless steels are expected to have greater durability, long-term reliability and lower maintenance, reconstruction and modernization costs for bridges. At the same time beautiful modern architectural solutions can be applied. The main obstacle to the use of stainless steel was the high initial material cost, which limited its use primarily to special and prestigious structures. Better information on additional benefits of stainless steels and the transition to long-term sustainability [1] brings wider use of stainless steel not only for handrails or bridge roller bearings [2], but also for structural components of decks and in suspension systems or in anchorage components [3].

The design of structural elements made of stainless steel differs in many aspects from carbon steel elements. The non-linear stress-strain characteristics of stainless steel [4] leads to a different structural response than when carbon steel is used [5]. During the analysis of the limit states of elements, it is possible to build on proven research principles of material and geometric characteristics of carbon steel



structural elements, which have been subjected to thorough experimental research in terms of both strength [6] and fatigue properties [7]. The results of experiments have been part of the theoretical research of structural reliability of elements [8], frame response [9], ultimate limit state [10], fatigue failures [11], fatigue limit states [12], life prediction [13], natural vibrations [14], buckling interactions [15] and the verification of design reliability conditions [16]. Computational models based on the finite element method [17] are investigated using statistical methods [18], sensitivity methods [19], the probabilistic analysis of reliability [20] and processed by MCDM methods [21]. Although a significant part of the theoretical basis of standard EN1990 can be applied to assess the reliability of stainless steel load-bearing elements, there is sufficient diversity of the physical properties of carbon steel and stainless steel that require separate processing in the structural design. In addition to direct differences in fundamental material properties, such as the non-linear stress-strain curve and the corresponding yield strength and Young's modulus, there are other important differences in the material's response to cold-work and elevated temperatures [22].

## 2. Material and geometrical properties

Structural properties are influenced by many imperfections associated with material, geometry, environmental effects, load actions, etc., which are random in nature [23]. If a structure is to perform its functions reliably, this must be taken into account during design. The non-linear dependence of stress vs strain and other differences between the physical properties of carbon steel and stainless steel may also result in the occurrence of special phenomena whose influence on structural reliability is not currently a common part of design. In the general classification of initial structural imperfections [24], three basic categories of imperfections can be considered.

- 1) Geometric deviations: initial axial curvature of the bar, eccentricity of loading, failure to observe the theoretical arrangement of the cross-section (tolerance of cross-section dimensions and shape), etc.
- 2) Structural defects: dispersion of the mechanical properties of materials (material inhomogeneity manifested by the variance of designated values of the yield strength, ultimate strength, modulus of elasticity, etc.), initial stress state (residual stress due to rolling, welding, straightening and other technological production processes).
- 3) Structural imperfections: imperfections in joints, connections, bearings and other construction details reflected in deviations from the actual load bearing system compared to the theoretical assumptions introduced when solving an idealized system.

The fundamental problem here is the determination of the initial imperfections and the analysis of their influence on the limit states and other structural properties, which are necessary in the creation of computational models. Computational models for the analysis of the ultimate limit state of resistance and the serviceability limit state of slender members under compression require the inclusion of both material and geometric non-linearity.

## 3. Stress–strain curves

The non-linear stress–strain behaviour can be analytically described using a suitable material model [25]. The most widely used models are based on the general expression, which was originally proposed by Ramberg and Osgood [26] and modified by Hill [27], given by (1):

$$\varepsilon = \frac{\sigma}{E} + 0.002 \left( \frac{\sigma}{\sigma_{0.2}} \right)^n \quad (1)$$

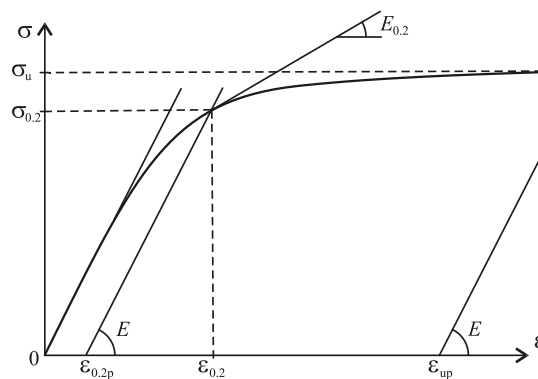
where  $E$  is Young's modulus,  $\sigma_{0.2}$  is the 0.2% proof stress typically considered as the yield stress, and  $n$  is the strain hardening exponent, which can be determined as:

$$n = \frac{\ln(20)}{\ln\left(\frac{\sigma_{0.2}}{\sigma_{0.01}}\right)} \quad (2)$$

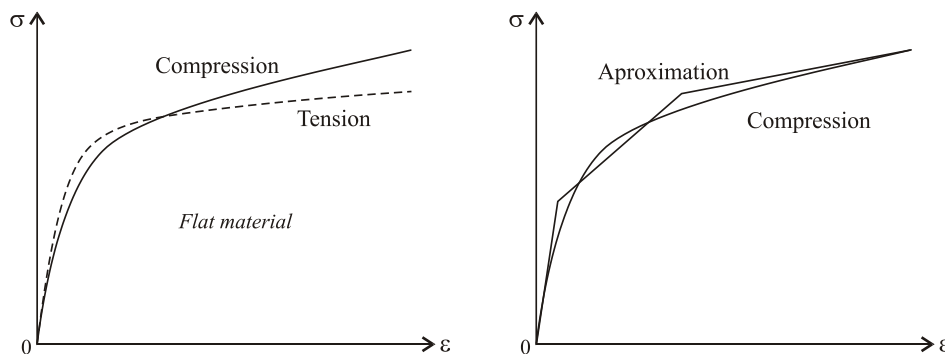
The ultimate strength  $\sigma_u$  and ultimate plastic strain  $\varepsilon_{up}$  must be suitably captured for an accurate representation of the material to be achieved, see Figure 1. The tangent modulus  $E_{0.2}$  at the 0.2% proof stress is given by (3).

$$E_{0.2} = \frac{E}{1 + 0.002n \frac{E}{\sigma_{0.2}}} \tag{3}$$

The use of other material models [25] can be investigated in order to approximate the random variability of the stress–strain curves. One possible approach may be to approximate the concave curve in piecewise linear segments, see Figure 2.



**Figure 1.** Stress–strain curve with definitions of key material properties.



**Figure 2.** Stress–strain curves of stainless steel.

The design resistance is determined as the load at which the yield strength  $\sigma_{0.2}$ , which is determined by the established industrial practice as 0.2% proof stress  $\sigma_{0.2}$ , is reached at the most stressed section [25, 28]. The yield strength is also the index of the elastic limit of steel. The evaluation of yield strength as a random variable based on experiments shows the importance of accurate determination of the initial gradient of the stress-strain curve. It is apparent from equation (2) that if  $\sigma_{0.01} < \sigma_{0.2}/20$ , the stress-strain curve may be a convex function, which is unrealistic. The statistical characteristics differ between austenitic, duplex and ferritic grades of stainless steel and therefore the effect of material grade of stainless steel on the resistance and deformation must be taken into account by dividing data on structural performance, for e.g. into subsets [29]. It can be noted that basic sets of measured characteristics are more valuable than summarizing statistical data supplemented by conclusions that are poorly supported with detailed numerical studies based on stochastic models.

#### 4. Numerical modelling

Compressive loading of bar elements is more complicated than tensile loading or bending because, in addition to material non-linearity, geometric non-linearity along with inevitable initial imperfections must be taken into account. The basic model for the calculation of the load-carrying capacity of a member under compression can be developed using the analytical solution of the strut resistance [24], which assumes a compressed member with initial axial curvature in the shape of a half-wave of the sine function with small initial amplitude  $e_0$ . As a result of the compressive force  $F$ , the initial imperfection increases from  $e_0$  to  $e$  according to the equation:

$$e = \frac{e_0}{1 - \frac{F}{F_{cr}}} \quad (3)$$

where  $F_{cr}$  is Euler's critical load. Equation (3) can be modified to an incremental form that is suitable for the analysis involving the non-linear shape of the curve in Figure 1. In one small load step, it can be assumed that the stress-strain dependence is linear. Under this assumption, it is possible to compute, taking into account (3), the elastic deformation increment  $e_{i+1}$  from the small load increment  $\Delta F = F_{i+1} - F_i$  using equation (4):

$$e_{i+1} = \frac{e_i}{1 - \frac{\Delta F}{F_{cr}}} = \frac{e_i}{1 - \frac{F_{i+1} - F_i}{F_{cr}}} \quad (4)$$

From a certain stress level, the compressive force  $F_i$  begins to decrease, which means that  $\Delta F$  is negative. Therefore, it is more practical to have a deformation step instead of a force step, for which  $\Delta e = e_{i+1} - e_i > 0$  always holds. The load increment step, depending on the deformation increment, can be obtained by modifying (4) as

$$\Delta F = F_{cr} \frac{e_{i+1} - e_i}{e_{i+1}} = F_{cr} \frac{\Delta e}{e_{i+1}} \quad (5)$$

Due to the increment of deformation  $\Delta e$ , the moment condition of equilibrium from the already transferred load  $F_i$  with corresponding deformation  $e_i$  is violated. In the previous  $i^{\text{th}}$  step, the bending moment  $M$  from load  $F_i$  was:

$$M = F_i e_i \quad (6)$$

It is essential that the bending moment from the transferred load  $F_i$  has the same value even after the deformation has increased from  $e_i$  to  $e_{i+1}$ . Therefore, it is necessary to reduce the transferred load  $F_i$  by the residual force denoted as  $F_{i,cor}$ . In other words, it is necessary to determine the residual force  $F_{i,cor}$ , by which it is necessary to reduce the already transferred load  $F_i$  so that the moment condition of equilibrium is fulfilled even after increase in deformation from  $e_i$  to  $e_{i+1}$ :

$$M = F_i e_i = (F_i - F_{i,cor}) e_{i+1} \quad (7)$$

The residual force  $F_{i,cor}$  can be derived from (7) as

$$F_{i,cor} = F_i \frac{\Delta e}{e_{i+1}} \quad (8)$$

The residual force determines the correction of the already transferred load due to the increase in deformation by  $\Delta e$ . The total force obtained  $F$  is then determined from (8) and (5) as

$$F = \Delta F - F_{i,cor} = (F_{cr} - F_i) \frac{\Delta e}{e_{i+1}} \quad (9)$$

This approach is based on the increment of the deformation  $\Delta e$ , which also effectively enables the analysis of the downward branch of the working diagram when the loading force  $F$  decreases. This can

occur as a result of increasing the compressive stress of the slender column in combination with the decreasing stiffness of the cross-section. The result is a non-linear dependence of  $F$  vs.  $e$  from geometric and material non-linearity. This approach extends the possibilities of geometric and material non-linear analysis of the resistance described in [24] to the material non-linearity of stainless steels, which is an essential part of the analysis of the limit states of slender bars of stainless steel.

The shapes of the curves  $F$  vs.  $e$  depend on the slenderness of the columns and the size of the amplitude of initial curvature  $e_0$ , which is generally a random variable. Global sensitivity analysis methods have identified a large influence of  $e_0$  on the resistance of carbon steel columns with intermediate slenderness [30]. The design quantile of resistance is much more sensitive to  $e_0$  than the average resistance is to  $e_0$  [19]. The results of the sensitivity analysis of the resistance of members from carbon steel grades S235 and S335 should be supplemented with the analysis of the resistance of stainless steel structural elements and the mutual agreements and differences, in particular between the results of Sobol sensitivity analysis and quantile-oriented global sensitivity analysis of design resistance, which clarify the probabilistic background of the design conditions of reliability of standard EN1990 that are essential for reliable design according to limit states, should be verified.

## 5. Conclusions

The path to sustainable construction of buildings and bridges means a gradual transition from established technical solutions to the application of modern materials, technologies, and new methods of evaluating and assessing the reliability of buildings. The reliability of buildings is divided into safety and usability, where safety is related mainly to the ultimate limit state of load-bearing elements. Differences in the reliability assessment of load-bearing structural members of carbon steel and stainless steel, which are increasingly used in bridge structures, are discussed in the article. Stainless steel differs from commonly used carbon steel mainly in its material properties. The non-linear stress-strain curve of stainless steels requires that the limit state analysis of slender compression columns with imperfections include both material and geometric non-linearity. The article summarizes basic analytical approaches adapted for modelling the stress-strain curve in combination with geometric non-linearity of imperfect stainless steel bars. It is evident that the analysis of the limit states of load-bearing stainless steel structural members is more demanding both in terms of experiments and numerical models for which experimental material and geometrical characteristics are the basic input data and may, therefore, have an influence on the accuracy of the results of reliability assessments.

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