26th International Conference
ENGINEERING MECHANICS 2020
Brno, Czech Republic, November 24 – 25, 2020

MATERIAL MODEL PARAMETER IDENTIFICATION OF STAINLESS STEEL (AISI 304L)

Jindra D.*, Kala Z., Seitl S.*** , Kala J.******

Abstract: *Identification of Ramberg and Osgood nonlinear material model parameters for hot rolled stainless steel material grade 1.4307 (AISI 304L) was conducted. Reference data (stress-strain relation) were obtained from experimental program performed on normalized specimens. Parametrical numerical finite element model was created using commercially available software ANSYS classic APDL, and the subsequent optimization process was conducted in the environment of OptiSLang software.*

Keywords: Stainless steel, Finite element numerical model, Parameter identification, Ramberg and Osgood model.

1. Introduction

In comparison with an ordinary carbon steel, a test data of a stainless steel are less numerous. Unlike the standard carbon steels, the study stainless steel has no sharp yield point and possess a rounded stress-strain curve, with a higher ductility. In a conventional steel design, 0.2 % proof stress is used as the equivalent of the yield stress. However representation of the stress-strain behavior by a bi-linear material model (considering sufficient reliance in the design) does not recognize the significant material hardening, and therefore would result in a low cost effectivity due to a much higher stainless steel expenses.

The aim of this contribution is to identify the Ramberg and Osgood material model parameters of the stainless steel material grade EN 1.4307 (AISI 304L; hot rolling mill process). The reference for this process is the stress-strain curve obtained from the experimental uniaxial tension test (using normalized test specimen) [ASTM].

2. Experimental tests in uniaxial tension

A chemical composition of the stainless steel material in the table below is based on manufacturer attestation, and depicts an averaged value of 8 test specimens.

Tab. 1: Chemical composition of the test specimen (based on mill certificate).

Grade	C [%]	Mn [%]	S [%]	P [%]	Si [%]	Ni [%]	Cr [%]	N [%]
1.4307/304L	0.0470	1.7463	0.0030	0.0394	0.1638	8.1925	18.1325	0.0916

Experimental tests in uniaxial tension have been conducted using 2 normalized test specimens (cylindrical shape) forged from one batch, and the results are summarized in the Fig. 1. The tensional loading has been conducted by displacement increasing with constant speed of 1 mm / min. For the further parameter identification process, curve marked as "specimen 2" (see Fig. 1.) has been considered as the reference curve (yet little number of the test results have been obtained in order to conduct a proper statistical

* Ing. Daniel Jindra: Institute of Structural Mechanics, Brno University of Technology, Veveří 331/95; 602 00, Brno; CZ, jindra.d@fce.vutbr.cz

** Prof. Ing. Zdeněk Kala, PhD.: Institute of Structural Mechanics, Brno University of Technology, Veveří 331/95; 602 00, Brno; CZ, kala.z@fce.vutbr.cz

*** Assoc. Prof. Ing. Stanislav Seitl, PhD.: Institute of Physics of Materials, Czech Academy of Sciences, Žižkova 22; 616 62, Brno; seitl@ipm.cz

**** Assoc. Prof. Ing. Jiří Kala, PhD.: Institute of Structural Mechanics, Brno University of Technology, Veveří 331/95; 602 00, Brno; CZ, kala.j@fce.vutbr.cz

evaluation, and the variation of the test results is so far also negligible). Values of engineering stress-strain reference curve have been transferred into true (logarithmic) stress-strain relation to be able for comparison with the results of finite element analysis.

Due to the sensitivity of the test machine, the initial value of stress (corresponding to the 0 strain) was approximately 10 MPa. Therefore the whole reference curve has been lowered considering this value for the purpose of the subsequent parameter identification process.

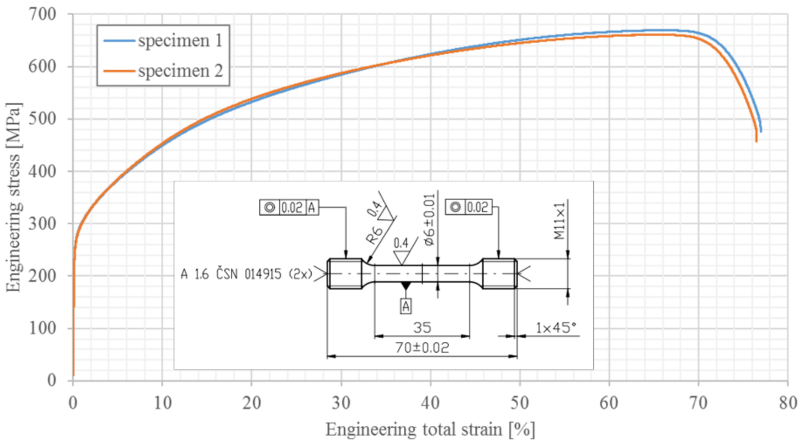

Fig. 1: Test specimen geometry, and measured stress-strain relation.

3. Numerical finite element model

A parametrical numerical finite element model has been created in the environment of ANSYS classic APDL (Ansys, 2018). In order to speed up the process of the parameter identification (where higher number of numerical analyses needs to be conducted), the whole geometry of uniaxial tension test has been simplified into one element uniaxial tension test. 3D 8 nodal solid element (SOLID 185) with 3 translational degrees of freedom at each node has been used (full integration).

3.1. Material model

The material model of stainless steel (304L) is described by a stress-strain relation proposed by Ramberg and Osgood (1943), modified by Hill (1944):

$$\varepsilon = \frac{\sigma}{E_0} + 0.002\left(\frac{\sigma}{\sigma_{0.2}}\right)^n , \tag{1}$$

where σ and ε are engineering stress and strain respectively, E_0 is the material elastic Young's modulus, $\sigma_{0.2}$ is the material 0.2% proof stress, and n is a strain hardening exponent. This formulation results in a very good agreement with stainless steel experimental data up to $\sigma_{0.2}$, however at higher strains the model overestimates the stress values (Gardner, 2001). A 2-stage compound stress-strain curve devised by Mirambell and Real (2000) provides better agreement with experimental data for stress values above the 0.2 % proof stress (Gardner, 2001). The second stage of the relation is given as:

$$\varepsilon = \frac{\sigma-\sigma_{0.2}}{E_{0.2}} + \left(\varepsilon_{tu} - \frac{\sigma_u-\sigma_{0.2}}{E_{0.2}} - \varepsilon_{t0.2}\right)\left(\frac{\sigma-\sigma_{0.2}}{\sigma_u-\sigma_{0.2}}\right)^{n'_{0.2,u}} + \varepsilon_{t0.2} \ldots for\ \sigma > \sigma_{0.2} , \tag{2}$$

where σ_u is the ultimate strength of the material, $n'_{0.2,u}$ is a strain hardening exponent, $\varepsilon_{t0.2}$ is the total strain at the 0.2 % proof stress, ε_{tu} is the total strain at ultimate stress, and $E_{0.2}$ is the stiffness (tangent modulus) at the 0.2 % proof stress given as:

$$E_{0.2} = \frac{E_0}{1 + 0.002\, n\, E_0\, /\, \sigma_{0.2}} \tag{3}$$

Eq. 2 is well applicable in tension, however in case of both types of loading, compression and tension, modification of the Eq.2 is proposed to be used (Gardner, 2004), where 1 % proof stress $\sigma_{1.0}$ is used instead of the σ_u, together with a corresponding strain hardening coefficient $n'_{0.2,1.0}$:

$$\varepsilon = \frac{\sigma-\sigma_{0.2}}{E_{0.2}} + \left(0.008 - \frac{\sigma_{1.0}-\sigma_{0.2}}{E_{0.2}}\right)\left(\frac{\sigma-\sigma_{0.2}}{\sigma_{1.0}-\sigma_{0.2}}\right)^{n'_{0.2,1.0}} + \varepsilon_{t0.2} \ldots for\ \sigma > \sigma_{0.2} . \tag{4}$$

For the purpose of the finite element (FE) numerical analyses, multilinear material model with isotropic hardening has been considered (Mises plasticity). In order to neglect the plasticity at low values of strain, the stress-strain behavior has been always considered as ideal elastic up to value of 2/3 $\sigma_{0.2}$. Between 2/3 $\sigma_{0.2}$ and $\sigma_{0.2}$, the relation in accordance with Eq. 1 has been adopted, where the corresponding stress-strain pairs have been determined in 25 points divided evenly by the stress values. The behavior between these points is considered as purely linear. For values higher than $\sigma_{0.2}$, model approaches which differed in the relation either according to Eq. 2 or Eq. 4 have been adopted. In both cases the highest value of determined stress is σ_u, and the corresponding stress-strain pairs have been determined in 45 evenly distributed points between the values $\sigma_{0.2}$ and σ_u. After the ultimate strength, the stress values are constant (softening is not applicable by the relations considered in this study). For both approaches (Eq. 1 + Eq. 2; and Eq. 1 + Eq. 4), the engineering stress-strain material curves (defined as an ANSYS array parameter) have been transferred into true stress and logarithmic strain dependences, to be in match with the results of geometrically nonlinear FE analyses.

4. Material parameter identification

In order to identify the material parameters, the optimization analyses using commercially available software OptiSLang (Dynardo, 2019) have been initiated. The objective of the optimization is to obtain the best match between the stress-strain curve (true-logarithmic variant) of FE analyses and the reference stress-strain curve (specimen 2 from the Fig. 1 after transformation into true stress and log strain relation). The part of the reference curve after its maximum at σ_u (softening) has been altered into a constant stress value. The “best-match” objective is defined as the minimization of the Euclidean norm of the difference between the reference curve and the stress-strain results obtained from the FE analyses. The norm has been evaluated at strain points corresponding to each 2.5 MPa of the modified reference curve (between 0 MPa and σ_u value), and at another 10 values of strain (evenly distributed) after the σ_u has been reached (the cut part of curve parallel to x axis – see Fig. 2).

An evolutionary algorithm has been chosen during the optimization process for all the cases of parameter identification processes. Cases #1 - #3 consider material behavior described by Eq. 1 + Eq. 4. In case #4 material described by Eq. 1 + Eq. 2 has been adopted. In case #1, the reference curve only up to the strain value of circa 1.2 % has been considered. Case #2 adopts the values of parameters $\sigma_{0.2}$ and n from #1 as constants, and considers the whole reference curve. Case #3 considers all material parameters as variables and refers to the whole reference curve as well, as the case #4.

5. Results

Adopted equations usually provide good agreement with test data up to the strains of 10 % (Gardner, 2004). When considering the initial shape of the stress-strain curve, the best match (see Fig. 2 right) has been achieved for case #1, where the values of stress-strain obtained from FE analysis are very close to the reference data up to strain value of circa 3 - 4 %. Therefore, these values would be rather recommended as an inputs for conventional steel design. In higher strains, the case #1 overestimates the material behavior. The other cases (#2 - #4) are globally in much better match with the whole stress-strain curve, however the initial part of lower strains in slightly overestimated, which would not be as convenient for the conventional steel design as the results of case #1.

Tab. 2: Identified material parameter values (stress and strain in engineering values).

Case	**Material parameter**							
	E_0 [GPa]	$\sigma_{0.2}$ [MPa]	$\sigma_{1.0}$ [MPa]	σ_u [MPa]	ε_{tu} [%]	n [-]	$n'_{0.2,1.0}$ [-]	$n'_{0.2,u}$ [-]
#1	191.896	257.188	294.741	701.820	-	10.284	1.712	-
#2	191.102	as #1	306.844	679.563	-	as #1	2.321	-
#3	190.857	260.416	305.567	679.193	-	11.301	2.220	-
#4	202.962	252.087	-	676.998	61.22	10.127	-	2.522

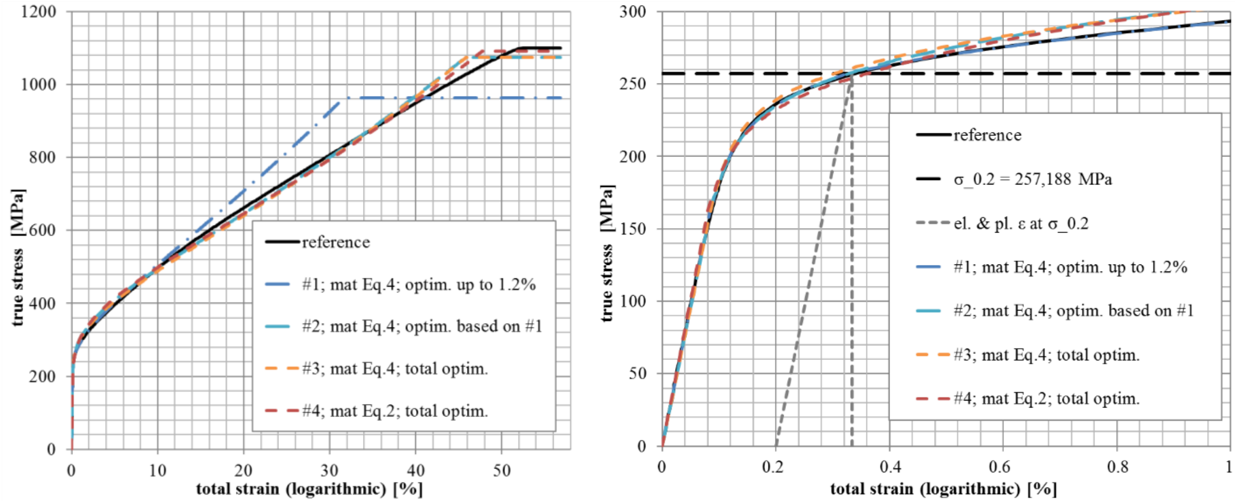

Fig. 2 Stress-strain curves (true-logarithmic) of the optimal designs; left - whole; right – zoomed part.

6. Discussion

For tension loads, the difference between adopting material behavior in accordance with Eq. 2 or Eq. 4 to determine the stress-strain values above the 0.2 % proof stress is not so evident. Both equations resulted in a similar values of input parameters (Tab. 2), which are in a nice match with other studies (Buchanan, 2018). According to the material attest (mill certificate), the mean value of circa 300 MPa is expected for $\sigma_{0.2}$. EN 3 (2008) determines the characteristic value of $\sigma_{0.2}$ for hot rolled stainless steel grade 1.4307 as 200 MPa. Adding the previously lowered value of 10 MPa (chapter 2) to the identified value of 257 MPa results in a nice agreement with the expectation.

7. Conclusions

The article presents a methodology that is applied in parallel with continuous experimental material testing of stainless steels. The objective was to identify the Ramberg and Osgood material parameters for stainless steel grade EN 1.4307 (AISI 304L), and the extended parameters proposed by Mirambell and Real (2000). Parameters have been identified and a nice match of FE analysis results with the reference data is observed.

Acknowledgement

This paper has been created with the financial support of Czech Science Foundation by project No.: 20–00761S "Influence of material properties of stainless steels on reliability of bridge structures".

References

Ansys, Inc. (2018) ANSYS 19.0. Canonsburg, PA 15317 U.S.A.

Buchanan, C., Real, E., Gardner, L. (2018) Testing, simulation and design of cold-formed stainless steel CHS columns. Thin-Walled Structures, 130: pp. 297-312. doi:10.1016/j.tws.2018.05.006.

ČNI. (2008) ČSN EN 1993-1-4 (731401) Eurokód 3: Design of steel structures - Part 1-4: General rules - Supplementary rules for stainless steels. Praha, (in Czech).

Dynardo GmbH (2019) ANSYS optiSLang 7.4.1. Weimar, Germany.

Gardner, L., Nethercot, D.A. (2001) Numerical modelling of cold-formed stainless steel sections, In: Mäkeläinen, et al., editors. Proceedings of the 9th Nordic Steel Construction Conference, Helsinki, Finland, pp. 781-789.

Gardner, L., Nethercot, D.A. (2004) Experiments on stainless steel hollow sections – Part 1: Material and cross-sectional behaviour. Journal of Constructional Steel Research, 60: pp. 1291-1318. doi:10.1016/j.jcsr.2003.11.006.

Hill, H.N. (1944) Determination of stress-strain relations from the offset yield strength values. Technical Note No. 927. National Advisory Committee for Aeronautics. Washington, DC.

Mirambell, E., Real, E. (2000) On the calculation of deflections in structural stainless steel beams: an experimental and numerical investigation. Journal of Constructional Steel Research; 54: 109-133.

Ramberg, W., Osgood, W. R. (1943) Description of stress-strain curves by three parameters. Technical Note No. 902. National Advisory Committee for Aeronautics. Washington, DC.