Comparative Study of Analytical Expressions for the Modelling of Stainless Steel Behaviour

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Abstract

Various material models have been proposed in last decades to describe stainless steel nonlinear behaviour through different parameters. The differences among these models are analyzed in this paper using experimental data for different types of stainless steel. An interactive program, usable for any series of experimental data, is developed to obtain the parameters needed for any material model, by means of a least-square adjustment. In addition, a procedure for the determination of the initial elastic modulus (E_0) is pointed out. Parameters proposed by several authors, considered in different codes for the modelling of stainless steel, have been compared and new values are suggested.

1 Introduction

Stainless steel is a relatively recent material that combines excellent corrosion resistance and mechanical properties suitable for structural applications. But its nonlinear stress-strain behaviour makes it different from carbon steel. Actual modelling techniques require defining an analytical expression to describe this nonlinear stress-strain relationship through a material model. In the literature, there are different analytical expressions which reproduce this behaviour [1-8] and all of them are based on the expression originally proposed by Ramberg-Osgood [9] and modified by Hill [10].

Those material models use some parameters that fit properly the behaviour of the stainless steel obtained from experimental tests. These parameters show a great variability between different stainless steel grades. Additionally, values for these parameters can be obtained from tables in Standards and from analytical expressions (previously calibrated for certain stainless steel grades). Results obtained from both methods are usually very different, but also when comparing them to experimental results. Hence, it is necessary to develop a tool for determining these parameters for the most relevant material models based on experimental data.

In this paper, a program which provides, from the experimental data, the values of the mechanical properties E_0, $\sigma_{0.2}$, σ_u, $\sigma_{0.01}$, $\sigma_{0.05}$, $\sigma_{0.1}$ and ε_u, and also the nonlinear coefficients which better fit different material models is briefly presented. The differences between these models are analysed in order to determine the most appropriate approach, and some expressions for the material parameters which fit properly the stress-strain behaviour for different stainless steel grades are suggested.

Although many authors have underlined that cold-working is a process which results in an increase in the yield stress and ultimate stress and causes important residual stresses [11-14], this preliminary study only covers annealed material coupons. Other researchers [15-17] have proposed two stage models for describing the stress-strain behavior of stainless steels at elevated temperaturest

2 Material Models and Standards

2.1 Existing material models

In last decades various material models have been developed in order to reproduce stainless steel behavior and some of them are included in European Standards. All these models have derived from the general expression proposed by Ramberg-Osgood [9] with Hill's modification [10]. The basic equation is presented in Eq. 1 where E_0 is the initial elastic modulus (material Young's modulus), $\sigma_{0.2}$, conventionally considered as the yield stress, is the proof stress corresponding to a 0.2% plastic strain.

$$\varepsilon = \frac{\sigma}{E_0} + 0{,}002\left(\frac{\sigma}{\sigma_{0.2}}\right)^n \qquad \text{(Eq. 1)}$$

The nonlinear parameter n is usually considered by the following expression:

$$n = \frac{\ln(20)}{\ln\left(\frac{\sigma_{0.2}}{\sigma_{0.01}}\right)} \qquad \text{(Eq. 2)}$$

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The Ramberg-Osgood expression provides accurate results working with stresses up to the yield stress, but when stresses increase, results become more inaccurate. In order to describe stainless steel behavior for higher stresses, Mirambell-Real [1] proposed a two stage model, based on the Ramberg-Osgood expression in which Eq. 1 is used for the range up to the 0.2% proof stress, but with a second curve for stresses over the 0.2% proof stress with a new reference system and different nonlinear parameter *m* on the second stage (Eq. 3).

$$\varepsilon = \frac{\sigma - \sigma_{0.2}}{E_{0.2}} + \left(\varepsilon_u - \varepsilon_{0.2} - \frac{\sigma_u - \sigma_{0.2}}{E_{0.2}}\right)\left(\frac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}}\right)^m + \varepsilon_{0.2} \quad \text{for} \quad \sigma > \sigma_{0.2} \qquad \text{(Eq.3)}$$

where $E_{0.2}$ is the elastic tangent modulus at 0.2% proof stress (Eq. 4), σ_u and ε_u are the ultimate stress and strain respectively, $\varepsilon_{0.2}$ is the total strain at the 0.2% proof stress, and *m* is the nonlinear parameter of the second stage.

$$E_{0.2} = \frac{E_0}{1 + 0.002n\dfrac{E_0}{\sigma_{0.2}}} \qquad \text{(Eq. 4)}$$

Rasmussen [2] revised this model for austenitc, ferritic and duplex stainless steels and proposed some simplifications in order to reduce the number of parameters needed to define the material model. The equation (Eq. 5) assumes that the ultimate plastic strain is equal to the total ultimate strain and some expressions to determine the second nonlinear parameter m (Eq. 6) and the ultimate strain ε_u (Eq. 7 and Eq. 8) using only the three basic Ramberg-Osgood parameters are also proposed in [2].

$$\varepsilon = \frac{\sigma - \sigma_{0.2}}{E_{0.2}} + \varepsilon_u \cdot \left(\frac{\sigma - \sigma_{0.2}}{\sigma_u - \sigma_{0.2}}\right)^m + \varepsilon_{0.2} \quad \text{for} \quad \sigma > \sigma_{0.2} \qquad \text{(Eq. 5)}$$

$$m = 1 + 3.5\frac{\sigma_{0.2}}{\sigma_u} \qquad \text{(Eq. 6)}$$

$$\varepsilon_u = 1 - \frac{\sigma_{0.2}}{\sigma_u} \qquad \text{(Eq. 7)}$$

$$\frac{\sigma_{0.2}}{\sigma_u} = \begin{cases} 0.2 + 185 \cdot \dfrac{\sigma_{0.2}}{E_0} & \text{for austenitic and duplex} \qquad \text{(Eq. 8a)} \\ \dfrac{0.2 + 185\dfrac{\sigma_{0.2}}{E_0}}{1 - 0.0375 \cdot (n-5)} & \text{for all stainless steel alloys} \qquad \text{(Eq. 8b)} \end{cases}$$

Rasmussen proposal has been included in Annex C of EN 1993-1-4 [18] for modeling stainless steel behavior.

Afterwards Gardner [3] proposed some modifications in the two stage model in order to have a more consistent model for compression. In this case, the second stage ends at the 1% proof stress. This model provides excellent agreement with measured stress-strain curves in both tension and compression and is accurate for the prediction of stress-strain behavior in structural purposes where strains are not very high.

$$\varepsilon = \frac{\sigma - \sigma_{0.2}}{E_{0.2}} + \left(\varepsilon_{1.0} - \varepsilon_{0.2} - \frac{\sigma_{1.0} - \sigma_{0.2}}{E_{0.2}}\right)\left(\frac{\sigma - \sigma_{0.2}}{\sigma_{1.0} - \sigma_{0.2}}\right)^{n0.2-1.0} + \varepsilon_{0.2} \quad \text{for} \quad \sigma > \sigma_{0.2} \qquad \text{(Eq.9)}$$

However, advanced numerical modeling requires a great knowledge of stainless steel behavior with a better fit of the stress-strain curves over a wide strain range, especially for cold-forming processes. Quach [5] proposed a three-stage material model, based in the true stress and strain values and using the three basic Ramberg-Osgood parameters, adequate for cold-formed materials. This model uses the Ramberg-Osgood equation for the first stage up to the yield stress, assumes the Gardner proposal (Eq. 9) for the second stage and proposes a new expression for the third stage up to the 2% true proof stress.

A new three-stage model, based on the Ramberg-Osgood equation for each stage but with a new reference system, has been developed by VTT (Finland), UPC (Spain) and Université de Liège (Belgium) [8]. This model has been developed to fit experimental curves up to the ultimate strain. Since the coupon tests analyzed in the present study are not cold-formed, the three-stage material model used is the one described in [8].

The main differences among these models lie in the definition of the end of the stress-strain curve and the number of parameters needed for their definition. The Ramberg-Osgood model is used for stresses up to 0.2% proof stress and uses one nonlinear parameter n; Mirambell-Real and Rasmussen models are defined for strains up to the ultimate strain ε_u and use two nonlinear parameters, n up to 0.2% proof stress and m for the second stage. The main difference between these two models is the number of material parameters needed for their definition; Mirambell-Real model needs 6 parameters while Rasmussen model needs only 3. As it has been explained before, Gardner model is defined up to 1% proof stress and uses also two nonlinear parameters. The three-stage material model has one stage for stresses up to 0.2% proof stress, other stage up to 1% proof stress and the last stage up to the ultimate stress σ_u and therefore uses three nonlinear parameters.

2.2 EN 1993-1-4

Expressions for the analytical description of the stainless steels behaviour proposed in EN 1993-1-4, Annex C [18] are derived from the Rasmussen material model (Eq. 5, 6, and 7), although instead of proposing an expression for the determination of the ultimate strength σ_u, EN 1993-1-4 provides σ_u values for different stainless steel grades. Values for $\sigma_{0.2}$ and E_0 are also proposed. The value of the nonlinear parameter n can be obtained either from (Eq. 2) or from Table 2.1 in EN 1993-1-4.

3 Test Data

In order to obtain the main parameters for each material model, data obtained from previous experimental tests carried out in UPC and Outokumpu have been analyzed. A total of 42 experimental stress-strain curves have been analysed in this study. Some of them have been already reported in the literature [19], [20] and [21]. The other ones where obtained directly from Outokumpu.

All the studied coupons were annealed, cut from plate elements and they are gathered in Table 1, showing the number of the total analysed coupons in each case and its origin.

Table 1 Analysed stainless steel coupons

Family	Grade	Number of coupons	Origin
Austenitics	1.4301	6	[19], [20]
	1.4301	6	Outokumpu
	1.4435	5	Outokumpu
	1.4541	5	Outokumpu
	1.4307	2	Outokumpu
Ferritics	1.4003	3	[21]
	1.4016	6	[21]
	1.4509	6	[21]
	1.4521	3	[21]

4 Explanation of the developed program

With the aim of obtaining, from the experimental data of any stress-strain curve, the value of the material properties and moreover the optimum value of the nonlinear parameters for the material models presented before, it is useful to develop a program that carries out all the complex calculations needed for optimization. The operations explained in this chapter have been scheduled in an Office Excel sheet with some required automatic processes by a VBA module. A more detailed explanation about this program can be found in [22].

4.1 Experimental data treatment

Some corrections should be made to avoid the changes in the stress-strain curve due to different strain rates during the tests. Moreover, other corrections are needed to determine correctly the initial elastic modulus because of the dispersion of the experimental data at the beginning of the curve, due to the measuring instruments accommodation.

The strain rate during a tensile test on a test specimen of stainless steel is often not constant during the whole test [23] and after reaching a plastic deformation of about 1.5% this rate increases considerably. This change in the strain rate causes a disturbance in the experimental data series, which is materialized by a small jump in the stress-strain curve. To use the experimental data it is necessary to remove this jump correctly and the program makes an automatically translation of experimental data previously defining a transition zone.

Later, the values of the material mechanical properties can be determined. The most important ones are the initial elastic modulus E_0, the yield stress $\sigma_{0.2}$ and the ultimate stress σ_u.

The calculation of the initial elastic modulus E_0 is performed by a linear regression on a set of representative points. The choice of this set of points is very important due to the sensitivity of the value of the initial elastic modulus to these representative points. The initial test data is not usually representative due to machine-coupon acomodation, so these points do not need to be considered in E_0 determination. Slope variations betweet 15-point-groups are calculated, and when three variations are lower than 0.5%, the acomodation process can be considered over (Fig. 1).

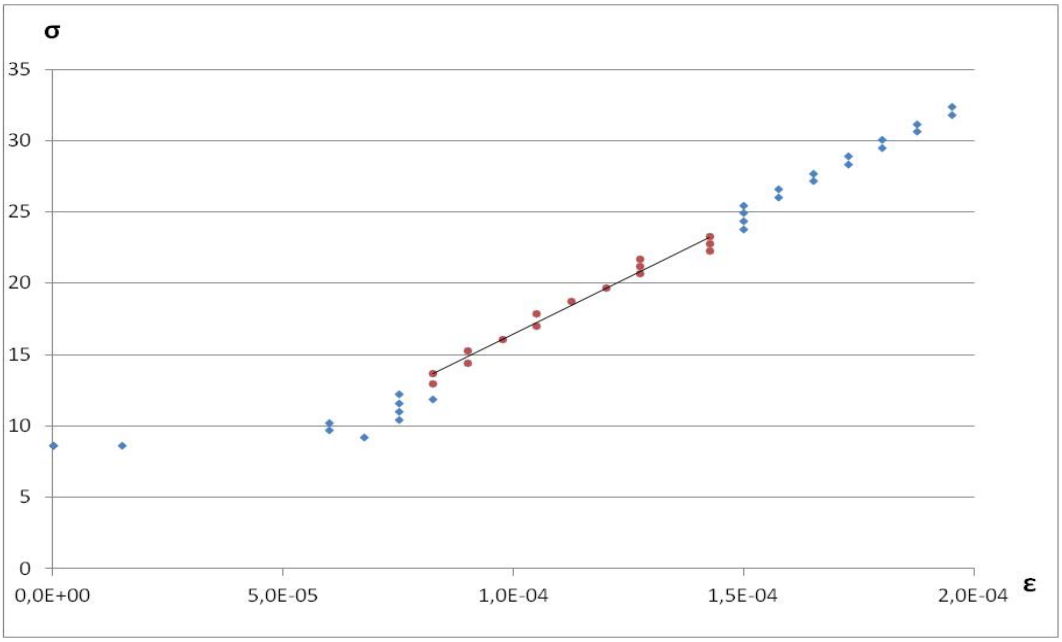

Figure 1 First point selection for the initial modulus determination

The last point needs to ensure enough considered points to provide a representative E_0 value but without being on the nonlinear stress-strain branch.

Moreover, for best accuracy, it is better to correct previously experimental data to make sure that the linear elastic branch starts at the origin of the reference system by a translation of the corrected experimental data. Once the value of the initial modulus is determined, the determination of stresses is very easy, so all the difficulty lies in the method used to find E_0.

4.2 Non-linear parameter optimisation

In order to analyse the differences among the material models presented before, the tool developed in this study enables to determine the optimum nonlinear parameters providing the best curve fitting between experimental and analytical results obtained from a least square adjustment and minimizing the error between both curves.

It is important to outline that the optimization range is different for each material model. The nonlinear parameter optimization for the Ramberg-Osgood model is for stresses up to the yield stress (parameter n), in Mirambell-Real and Gardner models is for stresses up to 1% proof stress (parameters n and m) and for the three-stage model is for stresses up to 5% proof stress (parameters $n_{0\text{-}0.2}$, $n_{0.2\text{-}1.0}$ and $n_{1.0\text{-}u}$).

An error expression, involving both strain and stress terms, has been developed (Fig. 2), and different data-point density along different strain values, due to changes in test-rates, has been also considered including Ci weights (Eq. 10). A more detailed description for the optimisation can be found in [22].

$$e = \sum_{i \in A} C_i \cdot \min_{k \in A} \left\{ \sqrt{ \left(\frac{\varepsilon_m(\sigma_i) - \varepsilon\ (\sigma_k)}{0.01} \right)^2 + \left(\frac{\sigma_i - \sigma_k}{\sigma_{1.0}} \right)^2 } \right\} \qquad \text{(Eq. 10)}$$

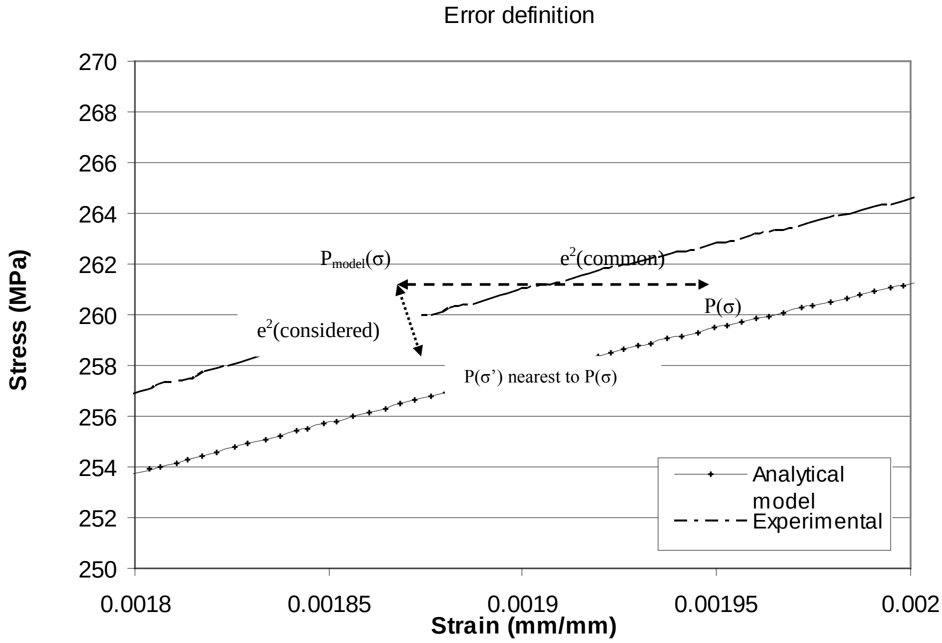

Figure 2. Error considered in the nonlinear parameter optimization.

5 Analysis of Results

5.1 Material model comparison

The developed program has been used to obtain the most important material parameters for each studied stainless steel grade. These parameters (E_0, $\sigma_{0.2}$, σ_{u}, $\sigma_{0.01}$, $\sigma_{0.05}$, $\sigma_{0.1}$ and ε_u) are automatically gathered in a table such as Table 2 for each coupon test analyzed from experimental data. The nonlinear parameters are optimised for each material model considered in the study (Table 3).

Table 2 Main material parameters provided by the program for a ferritic grade 1.4509 coupon test

Test					
			$\sigma_{0.01}$	245	*MPa*
ε_u	17,6%		$\sigma_{0.05}$	303	*MPa*
E_0	206 880	*MPa*	$\sigma_{0.1}$	320	*MPa*
			$\sigma_{0.2}$	331	*MPa*
			σ_u	464	*MPa*

Table 3 Nonlinear parameter optimization obtained by the program for each material model for a ferritic grade 1.4509 coupon test

Ramberg-Osgood	Mirambell-Real		Gardner		Rasmussen		Three-satge		
n	*n*	*m*	$n_{0\text{-}0.2}$	$n_{0.2\text{-}1.0}$	*n*	*m*	$n_{0\text{-}0.2}$	$n_{0.2\text{-}1.0}$	$n_{1.0\text{-}u}$
14.39	14.62	1.75	14.36	1.45	14.43	1.73	14.38	1.32	4.43

Experimental stress-strain curves are plotted beside the optimized ones for all the material models. Figure 3 shows an example of the plotted curves for the same ferritic grade coupon test presented in Tables 2 and 3.

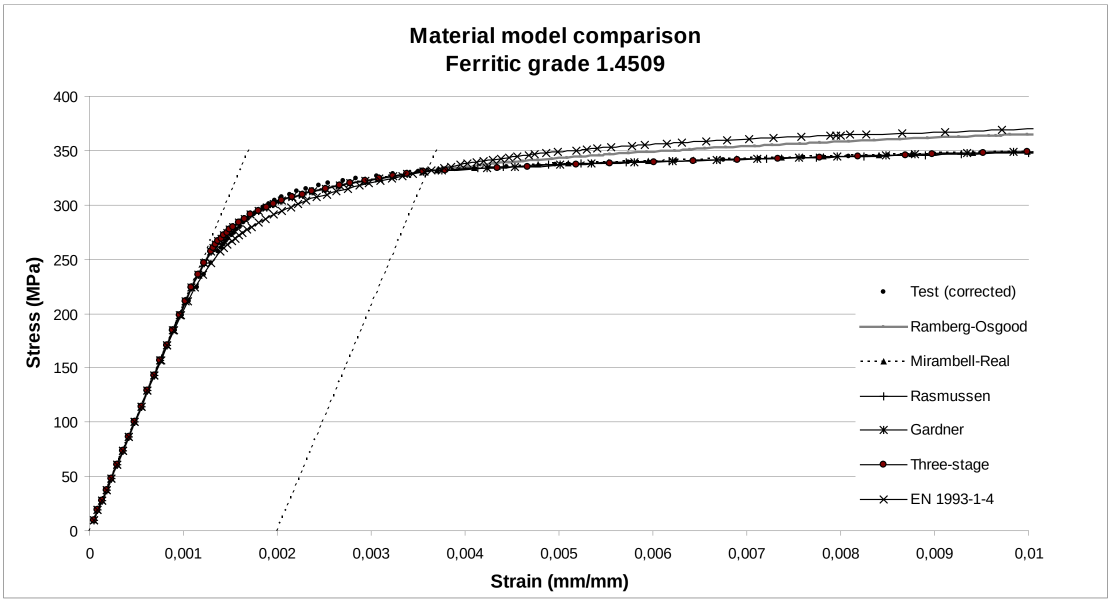

Figure 3 Experimental and optimized stress-strain curves for a ferritic grade 1.4509 coupon test.

Then, parameters and expressions proposed by several authors and considered in different codes could be compared with the experimental results, in order to check the accuracy and the applicability of the expressions defining most important material parameters as *n*, *m* and σ_u.

As it is shown in Table 2, a single value of the main material parameters is given for each test data. However, when working with the nonlinear parameters, different *n* and *m* values are provided derived from the optimization of each considered material model, as it can be seen in Table 3. In most of the studied cases, the optimized *n* and *m* values obtained for the Mirambell-Real [1], Gardner [3], Rasmussen [2] and three-stage [8] material models were very similar. The difference between these values is small because the optimization, up to 1% proof stress, is the same for the three models and then, although they have differences in the definition of the ultimate strain, the approaches up to 1% proof stresses are very close. On the other hand, the three-stage model is the one that better fits the experimental curve for strains over 1%, but this model needs more material parameters for their definition

5.2 Experimental material parameters

The experimental curves analyzed in this study have been used to check the expressions proposed in EN 1993-1-4 Annex C for stainless steel material modeling. A material characterization has been done for each experimental strain-stress curve analyzed. Results for different grades are presented in Tables 4 and 5 for the analyzed austenitic and ferritic stainless steels respectively. Although all nonlinear parameters from different material models are similar, *n* and *m* parameters obtained by the program when fitting Rasmussen material model are considered. This model needs only 3 parameters, the stress-strain equation is the same as the one proposed in EN 1993-1-4, Annex C and exhibits good agreement to experimental results for stresses up to 1% proof stress.

Table 4 Material parameters for the studied austenitic stainless steel grades

	E_0	$\sigma_{0.2}$	σ_{υ}	$\sigma_{0.01}$	$\sigma_{0.05}$	Nonlinear parameters		ε_u
	MPa	*MPa*	*MPa*	*MPa*	*MPa*	*n*	*%*	*%*
1.4301	193 823	301	630	210	260	9.48	2.64	41.7
	175 878	322	638	227	274	9.64	2.45	40.0
	191 658	323	604	203	272	9.21	2.35	39.0
	199 512	266	602	177	231	10.19	2.50	47.5
	194 422	300	598	177	255	8.08	2.35	44.5
	214 385	264	575	150	223	8.62	2.27	46.3
	185 893	293	634	203	252	9.26	2.50	44.3
	195 111	293	616	202	251	8.84	2.36	49.2
	165 973	274	638	216	248	13.47	1.82	52.6
	185 534	279	590	198	244	10.41	2.11	49.1
	164 805	258	649	208	234	14.41	1.86	52.7
	185 864	278	578	197	245	10.58	2.11	48.3
1.4435	185 804	322	592	184	291	12.49	1.94	41.6
	200 020	322	593	228	282	10.62	2.23	42.6
	189 126	322	598	238	291	13.64	2.11	42.4
	186 293	322	595	243	286	11.64	2.23	40.8
	186 718	322	597	240	285	11.52	2.20	41.7
1.4541	192 915	272	590	198	247	13.86	1.79	51.4
	182 249	270	594	197	237	10.47	1.98	48.0
	183 611	271	578	186	232	9.05	2.11	49.7
	191 698	276	581	196	239	9.83	2.20	45.8
	191 610	271	576	190	238	10.35	2.02	50.1
1.4307	192 590	293	605	205	256	9.26	2.50	48.6
	189 696	293	604	212	267	13.76	2.02	47.9
Average	**188 549**	**292**	**602**	**204**	**256**	**11.51**	**2.26**	**46.1**

Table 5 Material parameters for the studied ferritic stainless steel grades

	E_0 MPa	$\sigma_{0.2}$ MPa	σ_u MPa	$\sigma_{0.01}$ MPa	$\sigma_{0.05}$ MPa	Nonlinear parameters n	m	ε_u %
1.4003	219 855	328	479	203	292	10.68	1.78	16.0
	191 061	329	480	228	301	13.46	1.78	16.5
	198 330	330	479	203	297	11.72	1.76	16.8
1.4016	178 801	317	444	227	289	13.97	1.53	17.3
	167 301	315	446	255	293	18.50	1.69	17.8
	179 458	313	446	228	285	13.62	1.65	17.7
	195 781	311	467	218	280	12.74	1.81	16.9
	192 641	311	466	224	282	13.49	1.85	17.3
	191 016	309	467	216	279	13.18	1.85	17.3
1.4509	197 761	365	471	280	341	17.89	1.93	16.2
	190 842	367	472	303	345	21.73	1.66	16.4
	199 183	368	472	277	341	16.48	1.70	16.0
	203 557	331	463	241	303	14.74	1.70	18.3
	206 880	331	464	245	303	14.43	1.73	17.6
	202 781	331	463	242	303	14.32	1.72	17.6
1.4521	197 476	392	539	300	364	17.22	1.77	16.0
	197 286	394	550	309	367	18.21	1.85	16.0
	204 873	393	551	281	362	14.60	1.74	15.9
Average	**195 271**	**341**	**479**	**249**	**313**	**15.05**	**1.75**	**16.9**

Considering values obtained from the different tensile experimental stress-strain curves, and comparing them with the ones gathered in EN 1993-1-4, it is noticed that values proposed in EN 1993-1-4 are generally lower, specially $\sigma_{0.2}$ and *n* values, so they need to be revised in order to obtain a better material characterization. The value of the initial elastic modulus appears here lower than the value proposed in EN 1993-1-4 for austenitic and ferritic grades. Moreover, there are some ferritic stainless steel grades, such as 1.4509 and 1.4521, which are not considered in EN 1993- 1-4.

5.3 Expressions for the nonlinear parameter n

The accuracy of the classical expression proposed by Ramberg-Osgood [9] for the nonlinear constant *n* (Eq. 2) is checked herein. This constant is calculated by imposing that the original Ramberg-Osgood curve for stress up to 0.2% proof stress passes through the 0.01% and the 0.2% proof stresses.

As it has been previously demonstrated, those stainless steels have a less rounded shape than the one previously defined by the original Ramberg-Osgood equation (Eq. 1), it seems more adequate to use a higher stress value as 0.05% proof stress instead of 0.01% proof stress. Then the analytical expression for the nonlinear parameter *n* could be written as (Eq. 11).

$$n = \frac{\ln(4)}{\ln\left(\frac{\sigma_{0.2}}{\sigma_{0.05}}\right)} \quad \text{(Eq. 11)}$$

The accuracy of this new expression is analyzed in Tables 6 and 7 and in Figures 4 and 5 for each studied grade of austenitic and ferritic stainless steels respectively. In these tables, values of *n* obtained fitting the experimental curves with the Rasmussen equation for each grade are compared with values obtained with the original expression (Eq. 2) and the ones obtained with the new proposal (Eq. 11). It is important to outline that these experimental values were very similar to the ones obtained with the other material models.

Table 6 Experimental and analytical nonlinear parameter n values for austenitic stainless steels

	$\sigma_{0.2}$	$\sigma_{0.01}$	$\sigma_{0.05}$	**Optimised**	**Original (Eq.2)**		**Proposal (Eq.11)**	
	MPa	*MPa*	*MPa*	*n*	*n*	*Error (%)*	*n*	*Error (%)*
1.4301	301	210	260	9.48	8.26	12.90	9.40	0.91
	322	227	274	9.64	8.60	10.79	8.60	10.86
	323	203	272	9.21	6.43	30.16	8.00	13.05
	266	177	231	10.19	7.39	27.44	9.92	2.69
	300	177	255	8.08	5.67	29.85	8.55	5.89
	264	150	223	8.62	5.28	38.75	8.19	5.02
	293	203	252	9.26	8.13	12.24	9.28	0.19
	293	202	251	8.84	8.06	8.77	8.85	0.15
	274	216	248	13.47	12.64	6.11	13.54	0.54
	279	198	244	10.41	8.83	15.23	10.52	1.05
	258	208	234	14.41	13.98	2.94	14.24	1.18
	278	197	245	10.58	8.70	17.73	10.70	1.17
1.4435	322	184	291	12.49	5.36	57.10	13.53	8.30
	322	228	282	10.62	8.74	17.78	10.67	0.44
	322	238	291	13.64	9.94	27.17	13.45	1.38
	322	243	286	11.64	10.67	8.33	11.61	0.26
	322	240	285	11.52	10.23	11.24	11.46	0.52
1.4541	272	198	247	13.86	9.45	31.84	14.84	7.06
	270	197	237	10.47	9.41	10.07	10.51	0.39
	271	186	232	9.05	7.93	12.37	9.01	0.42
	276	196	239	9.83	8.73	11.22	9.81	0.21
	271	190	238	10.35	8.38	19.05	10.53	1.77
1.4307	293	205	256	9.26	8.41	9.15	10.14	9.46
	293	212	267	13.76	9.17	33.34	14.48	5.21
					Avrge.	*19.23*	*Avrge.*	*3.26*

Table 7 Experimental and analytical nonlinear parameter n values for ferritic stainless steels

	$\sigma_{0.2}$ MPa	$\sigma_{0.01}$ MPa	$\sigma_{0.05}$ MPa	Optimised n	Original (Eq.2) n	Original (Eq.2) Error (%)	Proposal (Eq.11) n	Proposal (Eq.11) Error (%)
1.4003	328	203	292	10.68	6.20	41.90	11.74	9.88
	329	228	301	13.46	8.12	39.66	15.23	13.12
	330	203	297	11.72	6.18	47.24	13.10	11.78
1.4016	317	227	289	13.97	9.02	35.46	15.16	8.47
	315	255	293	18.50	14.17	23.43	19.21	3.86
	313	228	285	13.62	9.44	30.71	14.70	7.95
	311	218	280	12.74	8.46	33.57	13.59	6.65
	311	224	282	13.49	9.15	32.19	14.22	5.43
	309	216	279	13.18	8.34	36.72	13.73	4.16
1.4509	365	280	341	17.89	11.27	37.01	19.90	11.24
	367	303	345	21.73	15.81	27.23	22.87	5.28
	368	277	341	16.48	10.57	35.84	18.12	9.98
	331	241	303	14.74	9.45	35.90	15.66	6.19
	331	245	303	14.43	10.02	30.53	15.73	9.01
	331	242	303	14.32	9.62	32.83	15.71	9.69
1.4521	392	300	364	17.22	11.17	35.18	18.44	7.03
	394	309	367	18.21	12.38	32.03	19.78	8.64
	393	281	362	14.60	8.90	39.02	16.72	14.57
					Avrge.	*34.80*	*Avrge.*	*8.50*

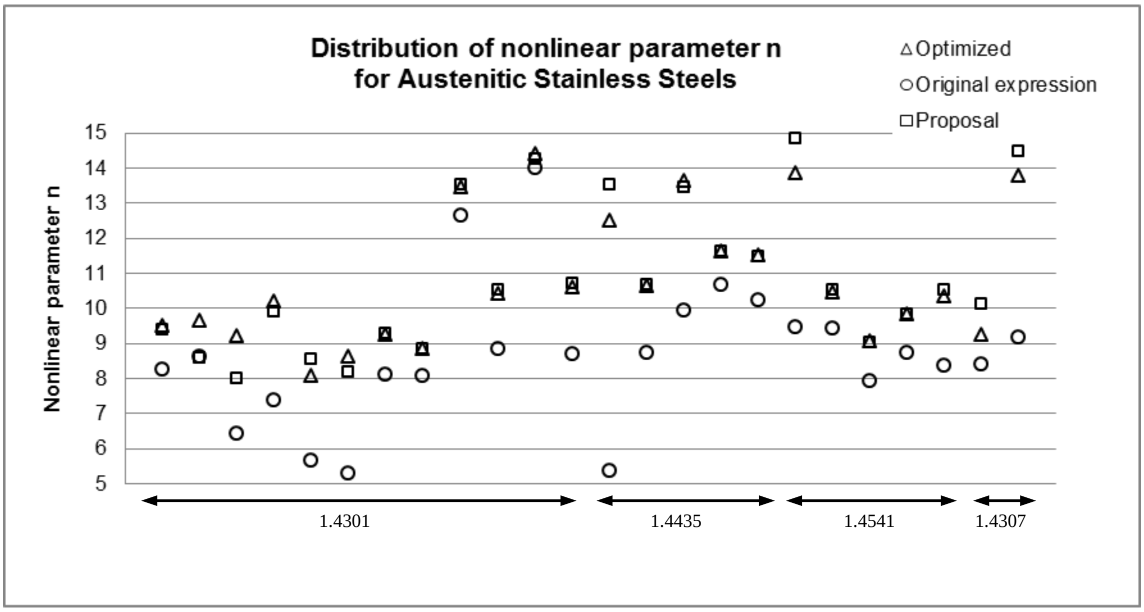

Figure 4 Experimental and analytical nonlinear parameter n values for austenitic stainless steels

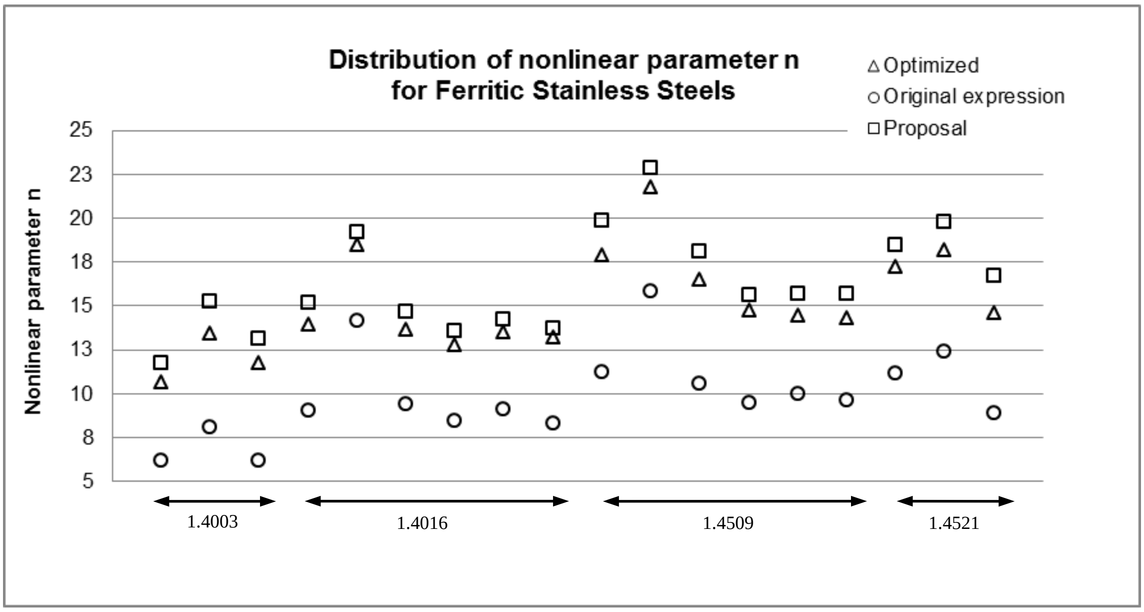

Figure 5 Experimental and analytical nonlinear parameter n values for ferritic stainless steels.

5.4 Expressions for the ultimate strength σ_u

Once all the material parameters are determined by the program, the values of the ratios $\sigma_{0.2}/\sigma_u$ obtained from the experimental curves can be analyzed. Figures 6 and 7 represent experimental values compared to the ones obtained by (Eq. 8a) for austenitic and duplex stainless steels, and by (Eq. 8b) for all stainless steel grades respectively.

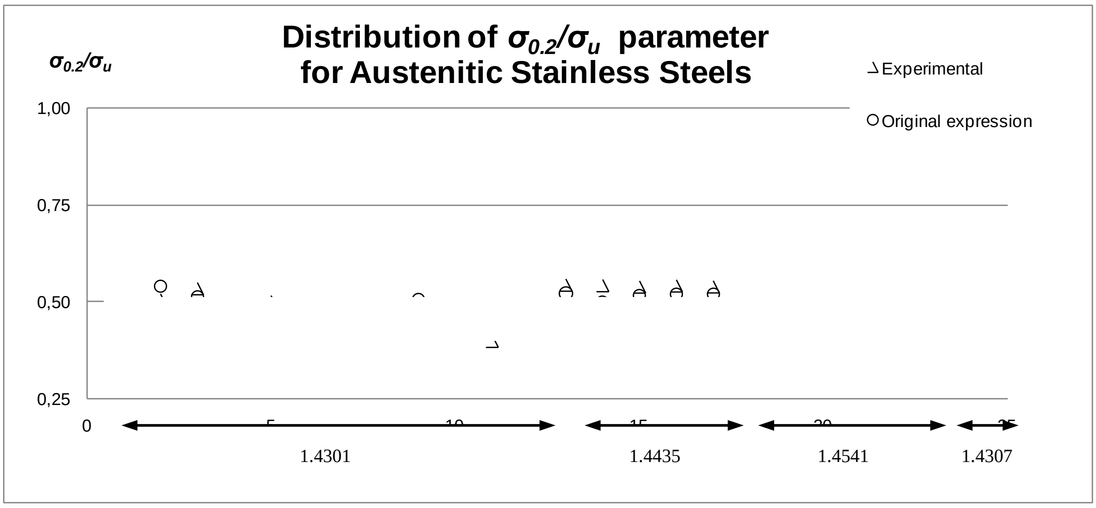

Figure 6 Experimental and analytical $\sigma_{0.2}/\sigma_u$ values for austenitic stainless steels.

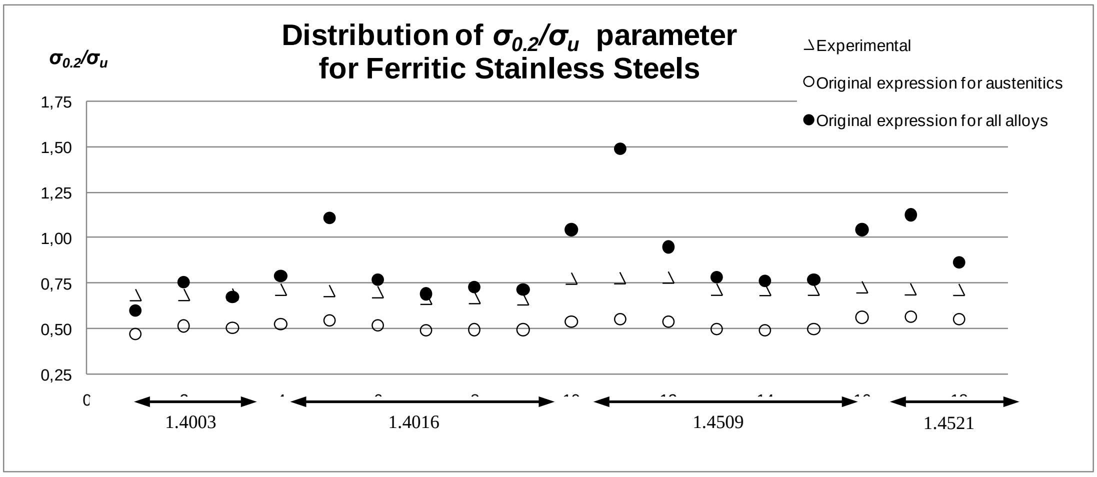

Figure 7 Experimental and analytical $\sigma_{0.2}/\sigma_u$ values for ferritic stainless steels.

Figure 6 shows that the original expression (Eq. 8a) is actually valid for annealed austenitic coupons. Figure 7 shows that the original expression for austenitic stainless steels (Eq. 8a) is not valid for ferritic stainless steels and the one covering all stainless steel grades (Eq. 8b) is quite good for the ferritic coupons tested. Anyway, as the original expression was not developed for the ferritic grades included in this study, the original nonlinear expression (Eq. 8b) can be simplified as a linear expression for ferritics (see Eq. 12 and Fig.).

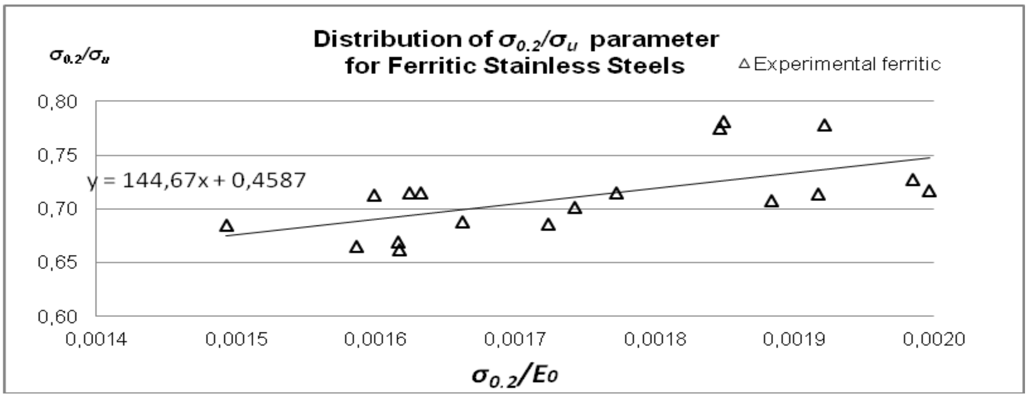

Figure 8 Linear approximation for $\sigma_{0.2}/\sigma_u$ values for ferritic stainless steels.

$$\frac{\sigma_{0.2}}{\sigma_u} = 0.46 + 145\frac{\sigma_{0.2}}{E_0} \qquad \text{(Eq. 12)}$$

Table 8 presents the differences between experimental and analytical $\sigma_{0.2}/\sigma_u$ values for the original and proposed expressions. As it is shown in the table, the new proposal provide a better agreement with the collected experimental data for all the ferritic grades, so (Eq. 12) can be a first approach to the adjusted $\sigma_{0.2}/\sigma_u$ expression for ferritic stainless steels.

Table 8. Experimental and analytical (original and new proposal) $\sigma_{0.2}/\sigma_u$ values for ferritic stainless steel

	Experimental	**Original for austenitics(Eq.8a)**		**Original all alloys (Eq.8b)**		**Proposal (Eq.12)**	
	$\sigma_{0.2}/\sigma_u$	$\sigma_{0.2}/\sigma_u$	*Error (%)*	$\sigma_{0.2}/\sigma_u$	*Error (%)*	$\sigma_{0.2}/\sigma_u$	*Error (%)*
1.4003	0.68	0.48	30.47	0.61	11.65	0.68	1.22
	0.69	0.52	24.34	0.76	10.83	0.71	3.53
	0.69	0.51	26.26	0.68	1.41	0.70	1.85
1.4016	0.71	0.53	26.09	0.80	11.39	0.72	0.39
	0.71	0.55	22.45	1.11	57.06	0.73	3.66
	0.70	0.52	25.44	0.77	10.17	0.71	1.71
	0.66	0.49	25.77	0.70	4.58	0.69	3.80
	0.67	0.50	25.39	0.73	9.45	0.69	3.82
	0.66	0.50	24.58	0.72	8.79	0.69	4.93
1.4509	0.78	0.54	30.12	1.05	35.23	0.73	6.10
	0.78	0.56	28.56	1.49	91.67	0.74	5.01
	0.78	0.54	30.58	0.95	21.90	0.73	6.75
	0.71	0.50	29.95	0.79	10.38	0.70	2.66
	0.71	0.50	30.45	0.77	7.58	0.69	2.95
	0.71	0.50	29.74	0.77	8.03	0.70	2.49
1.4521	0.73	0.57	22.04	1.05	43.95	0.75	2.78

	0.72	0.57	20.53	1.13	57.49	0.75	4.61
	0.71	0.55	22.26	0.87	21.43	0.74	3.42
		Avrge.	26.39	*Avrge.*	23.50	*Avrge.*	3.43

5.5 Expressions for the second nonlinear parameter m

Comparing values of the second nonlinear parameter *m* obtained in experimental stress-strain curve analysis with the ones calculated from the expression in (Eq. 6), some discordance can be observed. All the *m* values obtained with the original expression are too high for all the studied stainless steel grades, as shown in Tables 9 and 10 and in Figures 9 and 10 for austenitic and ferritic grades respectively. Some adjustments have also been proposed for the original expression for its application to austenitic (Eq. 13) and ferritic stainless steels (Eq. 14). Values from the new proposal are also gathered in Tables 9 and 10 and in Figures 9 and 10.

$$m = 1 + 2.3\frac{\sigma_{0.2}}{\sigma_u}$$ for austenitics (Eq. 13)

$$m = 1 + \frac{\sigma_{0.2}}{\sigma_u}$$ for ferritics (Eq. 14)

Table 9 Second nonlinear parameter m experimental and analytical (original expression and new proposal) values for austenitic stainless steels

	Optimised	Original (Eq. 6)		Proposal (Eq. 13)	
	m	*m*	*Error (%)*	*m*	*Error (%)*
1.4301	2.64	2.67	1.09	2.10	20.46
	2.45	2.77	12.90	2.17	11.66
	2.35	2.87	22.24	2.23	4.89
	2.50	2.55	1.94	2.02	19.15
	2.35	2.75	17.11	2.16	8.29
	2.27	2.61	14.96	2.06	9.19
	2.50	2.62	4.75	2.07	17.30
	2.36	2.67	13.12	2.10	10.97
	1.82	2.50	37.28	1.99	9.19
	2.11	2.65	25.95	2.09	0.78
	1.86	2.39	28.40	1.92	2.94
	2.11	2.69	27.20	2.11	0.00
1.4435	1.94	2.90	49.64	2.25	16.23
	2.23	2.90	30.06	2.25	1.04
	2.11	2.89	36.51	2.24	6.12
	2.23	2.90	29.79	2.25	0.85
	2.20	2.89	31.43	2.24	2.17
1.4541	1.79	2.61	46.02	2.06	15.34
	1.98	2.59	30.65	2.05	3.31
	2.11	2.64	25.15	2.08	1.33
	2.20	2.66	21.18	2.09	4.58

	2.02	2.65	30.89	2.09	3.13
1.4307	2.50	2.70	7.82	2.12	15.28
	2.02	2.70	33.54	2.12	4.90
		Avrge.	*24.15*	*Avrge.*	*7.88*

Table 10 Second nonlinear parameter m experimental and analytical (original expression and new proposal) values for ferritic stainless steels

	Optimised	**Original (Eq. 6)**		**Proposal (Eq. 14)**	
	m	*m*	*Error (%)*	*m*	*Error (%)*
1.4003	1.78	3.40	90.39	1.68	5.57
	1.78	3.40	90.60	1.69	5.50
	1.76	3.41	93.31	1.69	4.26
1.4016	1.53	3.50	128.32	1.71	11.83
	1.69	3.48	105.99	1.71	1.19
	1.65	3.45	109.38	1.70	3.14
	1.81	3.33	84.11	1.66	7.87
	1.85	3.34	80.55	1.67	9.81
	1.85	3.32	79.26	1.66	10.17
1.4509	1.93	3.71	92.68	1.78	7.88
	1.66	3.72	124.17	1.78	7.08
	1.70	3.73	119.57	1.78	4.74
	1.70	3.50	106.05	1.71	0.91
	1.73	3.50	102.43	1.71	0.79
	1.72	3.50	103.92	1.71	0.13
1.4521	1.77	3.55	100.12	1.73	2.52
	1.85	3.51	89.56	1.72	7.24
	1.74	3.50	100.67	1.71	1.69
		Avrge.	*100.06*	*Avrge.*	*5.13*

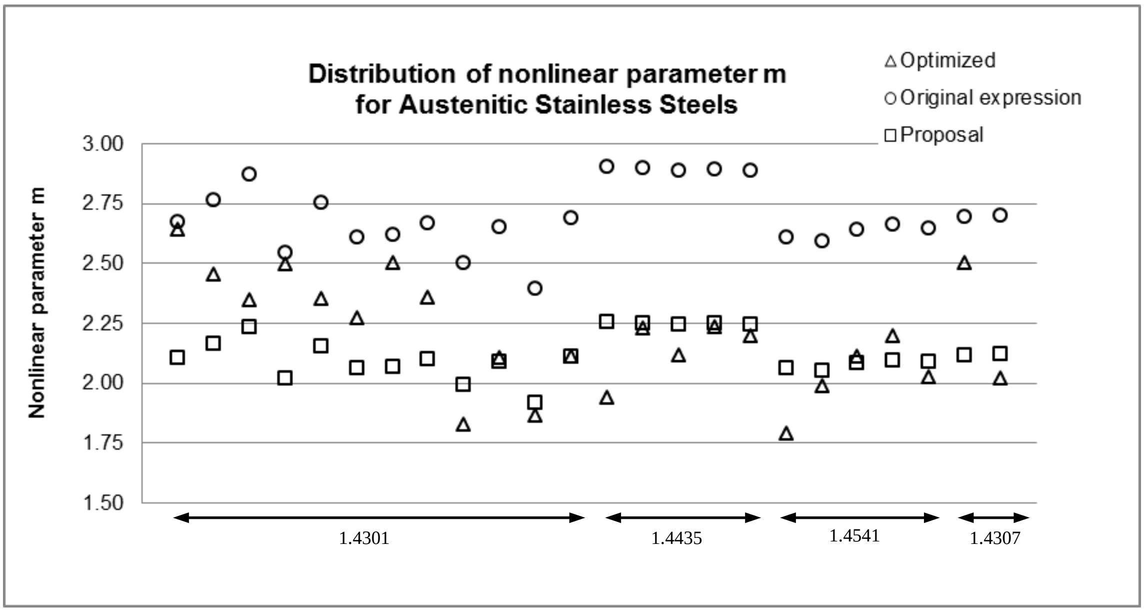

Figure 9 **Second nonlinear parameter m experimental and analytical (original expression and new proposal) values for austenitic stainless steels.**

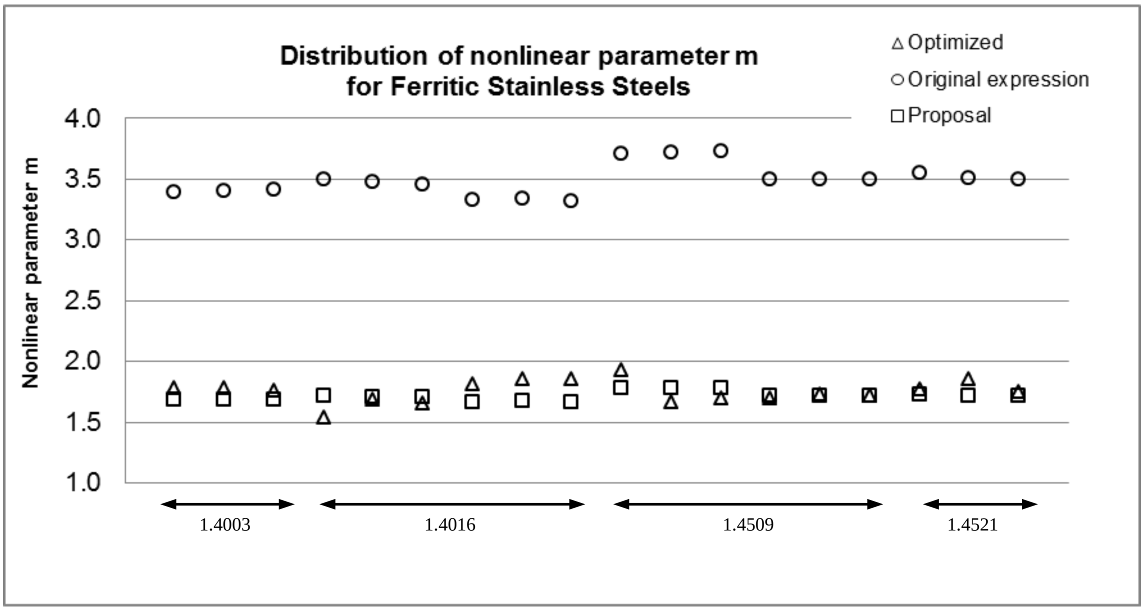

Figure 10 **Second nonlinear parameter m experimental and analytical (original expression and new proposal) values for ferritic stainless steels.**

The proposed new expressions provide more accurate *m* values, so the adjustment of the stress-strain curves predicted by the different models is better than the one obtained from the original expression, because analytical stress-strain curves are quite sensitive to *m* values, as it is shown in Figure 11 for a ferritic grade 1.4003.

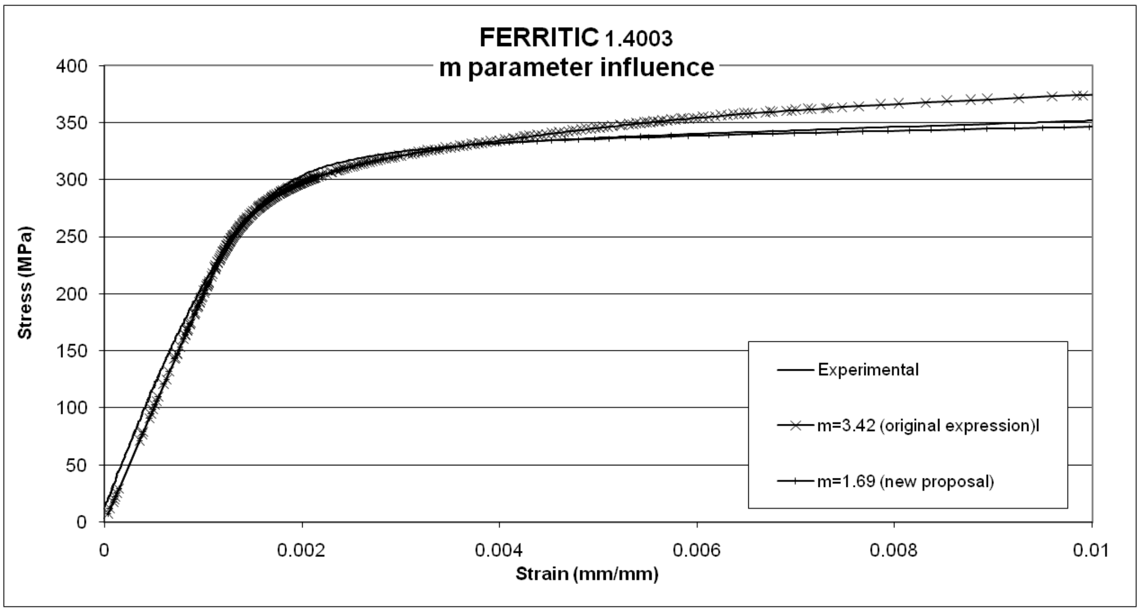

Figure 11 Stress-strain curves for the original and proposed *m* expression for ferritic grade 1.4003.

6 Conclusions

This paper presents an interactive program developed to obtain the main material parameters from experimental tensile-test data and the nonlinear parameters that better fit different material models for stainless steel. Some experimental data on austenitic and ferritic coupons from annealed stainless steel have been studied with the program.

Differences between the nonlinear parameters obtained from fitting the most relevant material models to experimental data are small. The experimental material parameters calculated with the program showed that material parameter values proposed in EN 1993-1-4 are not accurate enough.

Analysing the nonlinear parameters optimized by the program when fitting Rasmussen material model, new expressions for determining n and m non-linear parameters are suggested. These expressions are based on the equations presented in EN 1993-1-4, Annex C for stainless steel material modelling. A new linear approximation for $\sigma_{0.2} / \sigma_u$ for ferritic stainless steels has been also proposed.

These new proposals have been obtained from a limited number of test data, so further research needs to be done in order to adjust those proposals and extend their applicability to cold-formed stainless steel.

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