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Nonlinear Strain Hardening Parameter Comparison for Stainless Steel

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Abstract

Background/Objectives: To study about different models used for nonlinear analysis of stainless steel and to find an optimized equation for the nonlinear strain hardening exponent for stainless steel material. **Methods/Statistical Analysis:** There are lots of models proposed for analyzing the nonlinear behavior of the stainless steel. The base of all the models are model suggested by[1]. But there exist lots of uncertainties in Ramberg Osgood suggested equation for nonlinear strain hardening parameter, which is using proof stress at 0.01 and 0.2 strains. In 2014 [2]also proposed an equation for computing the nonlinear strain hardening parameter, which is using proof stress at 0.05 and 0.2 strains. The percentage error is less when compared with the Ramberg-Osgood equation, but still it shows some errors. In this work a new equation for nonlinear strain hardening model is developed using nonlinear regression technique with an optimized algorithm based on the comparative study of the above two models. **Findings:** A new equation for computing the nonlinear strain hardening parameter for stainless steel was proposed. The presently proposed equation for nonlinear strain hardening parameter is calculated by using proof stress corresponding to 0.01, 0.05 and 0.2 strains, which is showing excellent matching with the computer optimized values of nonlinear strain hardening exponent. The percentage errors with respect to the computer optimized values are very less when compared other models percentage errors. The Ramberg-Osgood equation is giving total error of thirty-five percentages; [2]model gives nearly nine percentages for ferritic stainless steel. Proposed model is showing an error percentage of two only. **Application/Improvements:** Proper nonlinear analysis of stainless steel is required for the economical use of sections and for getting more realistic assessment of the structural response of the material.

Keywords: Material Nonlinear Analysis, Nonlinear Strain Hardening Exponent N, Nonlinear Regression Analysis, Ramberg Osgood Model, Stainless Steel

1. Introduction

Stainless steel has better properties compared to normal carbon steel, like high resistance against corrosion due to chromium content, high stiffness, high strength, weld ability, durability and good fire resistance. In order to utilize the full property of stainless steel it is recommended to do proper analysis. The actual stress strain curve for the stainless steel is nonlinear, up to yield point stress is directly proportional to strain and material will regain its original shape after the removal of the load. This type of analysis is easy to perform but the actual behavior of the structure is not obtained. Linear analysis is only an approximation. So for getting the actual behavior of the structure and for the complete utilization of material properties it is suggested to go for nonlinear analysis. There are many types of stainless steel in industries based on different applications. Basically they fall into five basic groups classified according to their metallurgical structure. They are the austenitic, ferritic, martensitic, duplex and precipitation-hardening groups. The austenitic stainless steels and the austenitic–ferritic (duplex) stainless steels are generally the more used for structural applications.

This paper presents a comparative study of strain hardening parameter of[1]equation with equation proposed by[2], along with authors proposed equation. These values are

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compared with the optimized value of strain hardening parameter given by[2]. The stress values for the present study are cited from[2]. Since various material models are currently being used, strain hardening parameter values are optimized for the different models. They developed a computer program, which includes an automated routine that simplifies the optimization of these parameters. The strain-hardening exponent optimization is conducted by a least square modification that diminishes the error between the analytical models and experimental curve, giving the best curve fitting.

2. Literature Review

The modeling of the nonlinear behavior plays an important role for the economical use of the material. Stainless steel hardens more than normal carbon steel; so accurate assessment of material properties is required. Earlier times there are lot of models established for the investigation of stainless steel. All these models are using [1] equation up to yield stress, which is the first recognized model and far ahead the model is altered by[3]. In this section commonly adopted models for stainless steel are discussed briefly.

2.1 Ramberg-Osgood Model

Ramberg–Osgood equation is created to describe the non-linear relationship between stress and strain after the yield point. It is particularly useful for metals that harden with plastic deformation, showing a smooth and clear elastic-plastic changeover. The succeeding Ramberg-Osgood equation is the typical illustration of nonlinear behavior of materials.

$$\in = \frac{\sigma}{Eo} + 0.002\left(\sigma/(\sigma\, 0.02)\right)^{n} \quad (1)$$

Where ε is the strain at the stress value σ and $\sigma_{0.02}$ is the yield strength of the material, generally the 0.2% proof stress is considered as the yield stress. Eo is the preliminary elastic modulus of the material and *n* is the Ramberg-Osgood parameter (strain hardening exponent) which is the degree of the nonlinearity of the stress-strain curve. The initial term of the equation signifies the linear behavior and the second represents the nonlinear behavior. For low stress values, the nonlinear factor is not important when compared to the linear factor. The strain hardening exponent n describes the degree of roundness of the stress-strain curve; the lesser the value of n, the yielding will be more. Ramberg gives the equation (2) for the strain hardening exponent parameter *n*

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

Where $\sigma_{0.2}$ is the stress at 0.2% plastic strain (i.e. the 0.2% proof stress) and σ0.01 is the stress at 0.01% strain. Normally, the value of n will vary between 3 and 10 for stainless steels, 6 and 40 for aluminum alloys, and 20 and 60 for high strength steels.

2.2 Mirambell-Real

Ramberg–Osgood equation shows inaccuracies at high strains with the measured value of stress. The stresses are normally being over estimated. When the stresses increase, experimental and predicted stress–strain curves diverge each other. In order to analytically define the stainless steel behavior for higher stresses [4]introduced a new parameter m and they improved the Ramberg Osgood equation after the yield point as given in equation (3).

$$\varepsilon = \frac{\sigma - \sigma 0.2}{E0.2} + \left(\varepsilon_u - \varepsilon_{0.2} - \frac{\sigma u - \sigma 0.2}{E0.2}\right)\left(\frac{\sigma - \sigma 0.2}{\sigma u - \sigma 0.2}\right)^{m} + \varepsilon_{0.2} \quad (3)$$

For $\sigma > \sigma_{0.2}$

$$E_{0.02} = \frac{Eo}{1 + 0.002n\,\frac{Eo}{\sigma o.2}} \quad (4)$$

Where $E_{0.2}$ is the tangent modulus at 0.2% proof stress, which is given by equation (4), ε_u is the ultimate strain and the σ_u is the ultimate stress of the material. $\varepsilon_{0.2}$ is the strain at a proof stress of 0.2%. *m* is the strain-hardening coefficient which is using after yield stress. This equation gives decent agreement with the verified results, but its application is restricted to the modelling of tension characteristics of steel only.

2.3 Rasmussen

[5]Model is also the extension of Ramberg-Osgood. He adopted the basic equation up to the yield stress of the material and beyond yield used Mirambell and Real's proposed equation. He proposed that the nonlinear strain hardening exponent is computed on the basis of the 0.01% proof stress. [5]Suggested an equation for calculating the extra strain hardening exponent m, which is given by equation (6).

$$\varepsilon = \frac{\sigma - \sigma 0.2}{E0.2} + \varepsilon_u \left(\frac{\sigma - \sigma 0.2}{\sigma u - \sigma 0.2}\right)^m + \varepsilon_{0.2} \quad (5)$$

$$m = 1 + 3.5 \left(\frac{\sigma 0.2}{\sigma u}\right) \quad (6)$$

2.4 Gardner and Nethercot

[6]Recognized the limitation of Mirambell and Real's two-stage model, whose application is restricted to the explanation of tensile stress–strain behavior. It is because of its dependence on the ultimate stress and the equivalent strain. For compression members these parameters do not exist because of the necking characteristics.[7]Proposed that that the 1% proof stress and the equivalent strain can be used in place of the ultimate stress. The modified model by [8]is given by equation (7), which is adopted for stresses greater than yield stress.

$$\varepsilon = \frac{\sigma - \sigma 0.2}{E0.2} + \left(\varepsilon_1 - \varepsilon_{0.2} - \frac{\sigma 1 - \sigma 0.2}{E0.2}\right)\left(\frac{\sigma - \sigma 0.2}{\sigma 1 - \sigma 0.2}\right)^{n0.2\text{-}1.0} + \varepsilon_{0.2} \quad (7)$$

Where σ_1 is the proof stress equivalent to a 1% plastic strain. The total strain at the proof stress of 1% is denoted by $\varepsilon_1$and $n_{0.2-1.0}$ is the strain-hardening coefficient of the second stage for Gardner's model.

2.5 Real, Arrayago, Mirambell, Westeel

[1]Proposed new equations for the strain hardening parameter of Ramberg Osgood equations and higher order parameter m for ferritic and austenitic stainless steel. They developed a computer program, which includes an automatized routine that simplifies the optimization of these parameters. The strain-hardening exponent optimization is conducted by a least square modification that diminishes the error between the analytical models and experimental curve, giving the best curve fitting.

$$n = \frac{\ln(4)}{\ln\left(\frac{\sigma 0.2}{\sigma 0.05}\right)} \quad (8)$$

Where $\sigma_{0.05}$ is the proof stress corresponding to a 0.05% strain. The new m parameter values calculated from these proposals are expressed in equation (9) and (10)

$$m = 1 + 2.3 \left(\frac{\sigma 0.2}{\sigma u}\right) \text{ for austenitic} \quad (9)$$

$$m = 1 + \left(\frac{\sigma 0.2}{\sigma u}\right) \text{ for ferritic} \quad (10)$$

2.6 Other Models

[9]Presents a three-stage stress-strain model for stainless steels, which is capable of accurate predictions over the full ranges of both tensile and compressive strains. This model is used for three basic Ramberg–Osgood parameters, in first stage Ramberg–Osgood equation is used for the stress up to the yield stress. Modified Gardner proposed equation is used for the second stage and the third stage, stresses up to the ultimate strength the author proposes an equation based on the hypothesis that stress–strain behavior at high strains can be modeled as a straight line passing though the point of 2% proof stress and the ultimate strength.

[10]Proposed a theoretical model to match the different kinds of measured or already existing stress-strain models. Authors established a new 3-stage model which uses the Ramberg–Osgood equation for every stage, but with alternate reference systems. [11]Conducted a comparative study of diverse techniques for flaw segmentation in TOFD Images of austenitic stainless steel welds.

3. Material Model Adopted in the Present Study

[2]Studied the behavior of ferritic and austenitic stainless steel both experimentally and analytically. For present study of this paper we cited[2] stress values for proposing the best equation for nonlinear strain hardening parameter *n*. [1]Used the stress at 0.2% plastic strain and stress at 0.01% strain for the calculation of nonlinear strain hardening parameter, whereas[2] used proof stress at 0.2% and 0.05% strains. So for getting more precise results the nonlinear regression investigation is carried out using the proof stress at 0.01%, 0.05% and 0.2% strains. The proposed equation (11) is giving excellent results with experimental results and analytical values. The equation developed for present study is explained below.

$$N_{Proposed} = 0.71 + 0.24 * N_{R\text{-}O} + 0.735 * N_{Real} \quad (11)$$

Where.

$N_{Proposed}$ = Proposed strain hardening exponent

$N_{R\text{-}O}$ = [2]proposed strain hardening exponent

N_{Real} = [1]proposed strain hardening exponent

For the present study the unknown variable is taken as strain hardening parameter n and it is calculated from the strain hardening parameters suggested by[1,2], so for calculating the proposed equation proof stress at 0.01%, 0.05% and 0.2% strains are used.

Let X_1 be the nonlinear strain hardening exponent value suggested by[1], which is computed by using stress at 0.2% plastic strain and stress at 0.01% strain and X_2 be

Table 1. Regression table for parameter study of proposed model

TYPE OF STEEL	Ramberg-Osgood n value(X1)	Real n value(X2)	Optimized n value (Y)	X1*Y	X1^2	X1*X2	X2*Y	X2^2
FERRITIC STAINLESS STEEL	6.24	11.92	10.80	67.43	38.98	74.45	128.78	142.18
	8.17	15.59	13.46	109.96	66.74	127.32	209.78	242.91
	6.17	13.16	11.72	72.26	38.01	81.12	154.21	173.12
	8.97	14.99	13.97	125.32	80.47	134.48	209.42	224.73
	14.18	19.15	18.50	262.27	200.99	271.46	354.23	366.63
	9.45	14.79	13.62	128.77	89.39	139.86	201.48	218.83
	8.43	13.20	12.74	107.42	71.09	111.32	168.20	174.30
	9.13	14.16	13.49	123.15	83.34	129.29	191.05	200.57
	8.37	13.57	13.18	110.27	70.00	113.57	178.90	184.25
	11.30	20.38	17.89	202.16	127.69	230.32	364.64	415.44
	15.63	22.43	21.73	339.70	244.39	350.58	487.31	502.91
	10.55	18.19	16.48	173.80	111.22	191.86	299.82	330.98
	9.44	15.68	14.74	139.16	89.13	148.07	231.19	246.01
	9.96	15.68	14.43	143.68	99.15	156.18	226.33	246.01
	9.57	15.68	14.32	136.98	91.50	150.03	224.60	246.01
	11.20	18.71	17.22	192.86	125.44	209.51	322.12	349.93
	12.33	19.53	18.21	224.49	151.97	240.74	355.61	381.35
	8.93	16.87	14.60	130.38	79.75	150.67	246.33	284.66
AUSTENITIC STAINLESS STEEL	8.32	9.47	9.48	78.89	69.25	78.78	89.75	89.63
	8.57	8.59	9.64	82.61	73.43	73.59	82.79	73.75
	6.45	8.07	9.21	59.41	41.60	52.03	74.30	65.07
	7.35	9.83	10.19	74.94	54.09	72.27	100.13	96.56
	5.68	8.53	8.08	45.88	32.24	48.43	68.92	72.76
	5.30	8.21	8.62	45.68	28.08	43.53	70.80	67.47
	8.16	9.20	9.26	75.59	66.64	75.07	85.16	84.57
	8.06	8.96	8.84	71.21	64.88	72.17	79.21	80.28
	12.60	13.90	13.47	169.66	158.64	175.13	187.30	193.34
	8.74	10.34	10.41	90.93	76.31	90.34	107.66	106.96
	13.91	14.20	14.41	200.39	193.39	197.45	204.60	201.59
	8.70	10.97	10.58	92.02	75.65	95.42	116.07	120.36
	5.35	13.69	12.49	66.86	28.66	73.31	171.05	187.55
	8.68	10.45	10.62	92.16	75.31	90.70	110.99	109.23
	9.91	13.69	13.64	135.18	98.22	135.72	186.80	187.55
	10.64	11.69	11.64	123.88	113.26	124.44	136.10	136.72
	10.19	11.36	11.52	117.42	103.89	115.76	130.84	128.99
	9.43	14.38	13.86	130.76	89.01	135.65	199.29	206.74
	9.50	10.63	10.47	99.50	90.32	101.06	111.34	113.09
	7.96	8.92	9.05	72.03	63.35	71.01	80.74	79.60
	8.75	9.63	9.83	86.03	76.60	84.29	94.68	92.76
	8.44	10.68	10.35	87.32	71.17	90.07	110.50	113.98
	8.39	10.27	9.26	77.67	70.35	86.13	95.09	105.46
	9.26	14.92	13.76	127.39	85.71	138.11	205.28	222.56
Σ	**386.34**	**554.28**	**529.78**	**5093.46**	**3759.28**	**5331.31**	**7453.38**	**7867.39**

Table 2. Strain hardening parameter for ferritic steel

Grade of Steel	Stress 0.2	Stress 0.01	Stress 0.05	Optimized *n*	Ramberg		Real et al		Proposed	
					n (*eq 2*)	Error (%)	*n* (*eq 8*)	Error (%)	*n* (*eq 11*)	Error (%)
1.4004	328	203	292	10.8	6.24	42.19	11.92	10.41	10.97	1.57
	329	228	301	13.46	8.17	39.31	15.59	15.79	14.12	4.91
	330	203	297	11.72	6.17	47.39	13.16	12.27	11.86	1.17
1.4016	317	227	289	13.97	8.97	35.79	14.99	7.31	13.88	0.67
	315	255	293	18.5	14.18	23.37	19.15	3.50	18.18	1.74
	313	228	285	13.62	9.45	30.58	14.79	8.61	13.85	1.66
	311	218	280	12.74	8.43	33.82	13.20	3.63	12.43	2.41
	311	224	282	13.49	9.13	32.33	14.16	4.98	13.31	1.37
	309	216	279	13.18	8.37	36.52	13.57	2.99	12.69	3.72
1.4509	365	280	341	17.89	11.30	36.84	20.38	13.93	18.40	2.83
	367	303	345	21.73	15.63	28.06	22.43	3.20	20.94	3.66
	368	277	341	16.48	10.55	36.01	18.19	10.39	16.61	0.77
	331	241	303	14.74	9.44	35.95	15.68	6.41	14.50	1.64
	331	245	303	14.43	9.96	31.00	15.68	8.69	14.62	1.33
	331	242	303	14.32	9.57	33.20	15.68	9.53	14.53	1.46
1.4521	392	300	364	17.22	11.20	34.96	18.71	8.63	17.14	0.46
	394	309	367	18.21	12.33	32.30	19.53	7.24	18.01	1.07
	393	281	362	14.6	8.93	38.83	16.87	15.56	15.25	4.45
				15.06	9.89	**34.91**	16.32	**8.5**	15.07	**2.05**

the nonlinear strain hardening exponent value suggested by[2] and it is calculated by using proof stress at 0.2% and 0.05% strains. Y is the computer optimized output that is optimized strain hardening parameter. N is the number of sets of experimental data's. The equations for nonlinear regression analysis are given below. The values of X_1, X_2 and Y are given in Table 1.

$$\Sigma Y = a * N + b * \Sigma X_1 + c * \Sigma X_2$$

$$\Sigma X_1 * Y_1 = a * \Sigma X_1 + b * \Sigma X_1^{\,2} + c * \Sigma X_1 * X_2$$

$$\Sigma X_2 * Y_1 = a * \Sigma X_2 + b * \Sigma X_1 * X_2 + c * \Sigma X_2^{\,2}$$

By solving above three simultaneous equations unknown a, b and c can obtain. The final equation will be in the form of equation given below

$$Y = a + b * X_1 + c * X_2$$

4. Results and Discussions

Ramberg-Osgood equation (2) is used to find the Ramberg strain hardening parameter which depends on proof stresses at 0.01% and 0.2% strains. Strain hardening parameter is also calculated using equation (8) suggested by[2] using stress at 0.05% and 002 % of strain level. Along with these equations, the proposed equation is used to find the nonlinear strain hardening parameter. The percentage error with respect to optimized values for ferritic and austenitic stainless steels is shown in Table 2 and Table 3 respectively. Optimized values are calculated[2] by developing a computer program, which uses least square adjustment methods for minimizing the errors.

Ferritic stainless steel giving excellent results for the proposed equation for strain hardening parameter n. The

Table 3. Strain hardening parameter for austenitic steel

Grade of Steel	Stress 0.2	Stress 0.01	Stress 0.05	Optimized *n*	Ramberg		Real et al		Proposed	
					n (eq 2)	Error (%)	*n (eq 8)*	Error (%)	*n (eq 11)*	Error (%)
1.4301	301	210	260	9.48	8.32	12.22	9.47	0.13	9.66	1.91
	322	227	274	9.64	8.57	11.11	8.59	10.91	9.07	5.87
	323	203	272	9.21	6.45	29.97	8.07	12.41	8.18	11.14
	266	177	231	10.19	7.35	27.83	9.83	3.57	9.69	4.87
	300	177	255	8.08	5.68	29.73	8.53	5.57	8.34	3.21
	264	150	223	8.62	5.30	38.52	8.21	4.71	8.02	7.01
	293	203	252	9.26	8.16	11.84	9.20	0.69	9.42	1.77
	293	202	251	8.84	8.06	8.88	8.96	1.36	9.22	4.35
	274	216	248	13.47	12.60	6.50	13.90	3.23	13.95	3.53
	279	198	244	10.41	8.74	16.09	10.34	0.65	10.40	0.07
	258	208	234	14.41	13.91	3.49	14.20	1.47	14.48	0.45
	278	197	245	10.58	8.70	17.79	10.97	3.69	10.86	2.61
1.4435	322	184	291	12.49	5.35	57.14	13.69	9.65	12.06	3.46
	322	228	282	10.62	8.68	18.29	10.45	1.59	10.47	1.42
	322	238	291	13.64	9.91	27.34	13.69	0.40	13.15	3.60
	322	243	286	11.64	10.64	8.57	11.69	0.45	11.85	1.82
	322	240	285	11.52	10.19	11.52	11.36	1.41	11.50	0.19
1.4541	272	198	247	13.86	9.43	31.93	14.38	3.74	13.54	2.33
	270	197	237	10.47	9.50	9.23	10.63	1.57	10.80	3.17
	271	186	232	9.05	7.96	12.05	8.92	1.42	9.17	1.36
	276	196	239	9.83	8.75	10.97	9.63	2.02	9.88	0.56
	271	190	238	10.35	8.44	18.49	10.68	3.15	10.58	2.19
1.4307	293	205	256	9.26	8.39	9.42	10.27	10.90	10.27	10.87
	293	212	267	13.76	9.26	32.72	14.92	8.42	13.89	0.96
				10.78	8.68	**19.23**	10.86	**3.88**	10.77	**3.28**

Table 4. Strain hardening parameters for ferritic stainless steel grade 1.509

Models	Computer Optimized *n*	Ramberg Osgood		Real et al		Proposed	
		n	Error (%)	*n*	Error (%)	*n*	Error (%)
Ramberg Osgood	14.39	9.96	30.80	15.68	9.00	14.62	1.59
Mirambell–Real	14.62	9.96	31.89	15.68	7.28	14.62	0.00
Rasmussen	14.43	9.96	31.00	15.68	8.69	14.62	1.31
			31.23		**8.32**		**0.96**

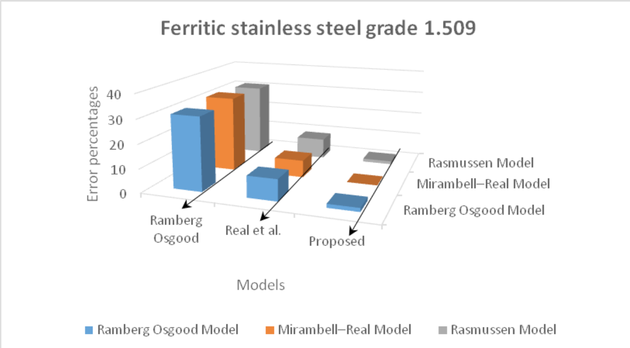

Figure 1. Percentage errors for strain hardening exponent for different models.

values are calculated for different grades of stainless steel. The percentage error with respect to the optimized values are very less when compared to[1,2] proposed equations percentage errors. The [1]is giving total error of thirty-five percentages, [2]model giving nearly nine percentages for ferritic stainless steel. Proposed model is showing error percentage of two only. So from the tables it is clear that proposed equation giving accurate reading for Ramberg parameter for ferritic stainless steel.

Austenitic stainless steel error percentages are very less when compared to Ramberg Osgood suggested values, by using Ramberg equation we are getting a total error of twenty percentages, while with proposed equation it shows very less percentage error for austenitic type of stainless steel.

The nonlinear strain hardening parameter for ferritic grade 1.509 stainless steel is shown in Table 4 and the percentage errors for different models is shown in Figure 1. Three models (Ramberg Osgood, Mirambell-Real, and Rasmussen) are compared for nonlinear strain hardening parameter by using equations proposed by[1,2] and proposed equation. [1]Equation is giving an error of thirty-two percentages, [2]Equation giving an error of nine percentages. The proposed equation is showing only an error of one percentage, which is negligible when compared to two other equations. So the proposed equation showing excellent results of ferritic and austenitic types of stainless steels.

5. Conclusions

In the present work a study of different models for the material nonlinear analysis of stainless steel was carried out. First proposed model for stainless steel was given by Ramberg-Osgood and all the other models are extension of Ramberg-Osgood equation. A new equation for computing the nonlinear strain hardening parameter for stainless steel was proposed using the proof stress corresponding to 0.01, 0.05 and 0.2 strains. The optimized nonlinear regression technique was used for development of the proposed equation by comparing the strain hardening exponent with models proposed by[1,2]. The results obtained by using proposed equation are showing excellent match with the nonlinear strain hardening exponent when compare with the computer optimized values.

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