

Stress–Strain Models for Stainless Steel

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Abstract

The non-linear stress–strain behavior of stainless steel alloys has often been described by the Ramberg–Osgood’s model, however, this model is only accurate up to the 0.2% proof stress. Advanced numerical analysis and design requires knowledge of the stress–strain relationship of the alloys over a full range of the stress–strain curves. To understand the potential of these models, this paper reviews different stress–strain models of stainless steel, in literature.

Keywords: Non-linear, stress–strain, stainless steel alloys, models.

1. Introduction

As a result of the vast difference in material properties between carbon and stainless steel it is necessary to determine an appropriate model for stainless steel alloys. Numerous models have been proposed to describe the non-linear behavior of stainless steel and these are briefly reviewed in this paper.

2. Early strain hardening model

Hill (Hill,1944) modified the Ramberg–Osgood model from determining the yield strength using the secant yield strength to the offset method. This meant that K and n could be evaluated using two offset yield strengths values. Hill suggested the commonly used value of 0.2%, and 0.1% (half of 0.2%) as offset values. If $\epsilon_1=0.1\%$ and $\epsilon_2=0.2\%$ are substituted into the Ramberg–Osgood equation, with the modulus of elasticity (E) equal to the initial modulus of elasticity (E_0), then the strain and strain hardening expressions would be as given in Equation 1.

$$\epsilon = f/E_0 + 0.002(f/f_{0.2})^n; n = \frac{0.301}{\log f_2/f_1} \quad (1)$$

The model is simple to use since it is based on three parameters, that is, the initial Young’s modulus (E_0), the proof stress ($f_{0.2}$) corresponding to the plastic strain (0.2%), and a strain hardening constant (n).

3. Recent strain hardening models

The anomaly with Hill’s (Hill,1944) modified Ramberg–Osgood model is that although it has been found to give excellent stress–strain predictions of stainless steel up to the 0.2% proof stress, it over-predicts the experimental stress–strain curves after this point. Thus it is unable to predict structural elements, such as plates in compression or shear, which undergo significant straining before reaching their ultimate capacity. Several authors have developed full-range stress–strain models to solve this anomaly.

MacDonald et al’s (MacDonald,2000) developed a model from austenitic (Type 304) stainless steel stub channel columns and coupons in tension only. It was found that the 0.2% proof stress and the 0.01% offset

stresses gave accurate results at low strains and relatively low nonlinearity indices (n), and higher values of the strain hardening exponent n should be used for higher strains. A simple trial and error approach was used to best-fit a curve to stress–strain data of the coupons, to give Equation 2.

$$\epsilon = f/E_0 + 0.002(f/f_1)^{i+j(f/f_1)^k} \quad (2)$$

Constants i , j and k are dependent on the thickness of the material tested and the exponent n is a function of stress. Although this expression was very accurate at high strains, its applicability was limited to a particular alloy and thicknesses tested, for which a suitable value for n has to be found from the experimental curve.

Olsson (Olsson,2001) performed a large number of tests on uniaxially and biaxially loaded coupons and observed that the stress–strain curve approached a straight line, at large strains, when the stress–strain curve was plotted as true stress against engineering strain. From these graphs Olsson approximated the true-stress vs engineering strain up to a total strain of 0.2% using the Ramberg–Osgood, and a straight line was used as a best fit after this point onwards. Olsson’s approach is simple to use, however, it lacks accuracy at small strains, since it assumes the Ramberg–Osgood curve for total strains up to 2%. The use of 0.2% and 1% proof stresses to determine n -parameter means that this method is not accurate enough for strains below the proof strain.

In the study of austenitic stainless (AISI 304) steel beams, Mirambell and Real (Mirambell and Real,2000) proposed a two-stage model for stainless steel stress–strain behaviour. The model adopted Ramberg–Osgood model for stresses up to the proof stress, however the strain hardening exponent (n) was determined using 0.2% and 0.05% proof stresses, instead of 0.2% and 0.01% proof stresses used in ANSI/ASCE-8-90. For stresses between the proof stress and the ultimate strength, a modified Ramberg–Osgood model, in Equation 3, was used.

$$\epsilon = \frac{f - f_{0.2}}{E_{0.2}} + \epsilon_U \left(\frac{f - f_{0.2}}{f_u - f_{0.2}} \right)^m + \epsilon_{0.2}; f > f_{0.2} \quad (3)$$

Parameter $E_{0.2}$ is the tangent modulus at 0.2% proof stress, $\varepsilon_{0.2}$ is the total strain at 0.2% proof stress, ε_u is the plastic strain at ultimate strength f_u and m is an additional strain hardening exponent. Note that parameter m is not related to n and need to be determined separately from the ultimate strength and another intermediate point. This equation agreed with tests results, however, the use of ultimate stress f_u and the corresponding strain ε_u , limits the application of the model to tension behaviour only. The curve defined by this equation produces a small inconsistency in that it does not pass through the point of (ε_u, f_u) , where ε_u is the total strain at ultimate stress, however, due to the high ductility of stainless steels, the errors incurred are negligible.

Rasmussen (Rasmussen,2003) developed a model exactly the same as Mirambell and Real's two stage model, however, in Rasmussen's model the strain hardening exponent n was determined, based on 0.2% and 0.01% proof stresses. Rasmussen is credited for developing the ultimate strength and strain expressions in terms of the three basic Ramberg-Osgood parameters, $f_{0.2}$, E_0 and n . Although the model is deemed to be applicable to all alloys in both tension and compression, the ultimate stress f_u , strain ε_u and strain-hardening exponent m were developed from tension coupons. This means that the model may not adequately apply to stainless steels in compression. Quach et al (Quach,2008) demonstrated that when the model is compared with measured stress-strain curves from literature (Macdonald et al. 2000; Rasmussen et al. 2002, 2003; Gardner and Nethercot 2004a), it provide excellent predictions for tension coupon tests, but significantly underestimate the stresses at strains for most compression coupon tests.

Gardner and Nethercot (Gardner and Nethercot,2004) recognised that Mirambell and Real's model (Mirambell and Real,2000) was limited to tensile stress-strain behavior (which includes necking) because of its reliance on the ultimate stress (f_u) and the corresponding strain (ε_u). Such a model would not work in specimens subjected to compression, where necking does not exist. Strains at ultimate strength (f_u) are far much higher than strains experienced by general structural systems. As in the previous models, Hill's Ramberg-Osgood model was used up to 0.2% proof stress. A new model (Equation 4), with 1% proof stress ($f_{1.0}$) was proposed in place of the ultimate stress (f_u) for stresses larger than 0.2% proof stress.

$$\varepsilon = \frac{(f - f_{0.2})}{E_{0.2}} + \left(\varepsilon_{1.0} - \varepsilon_{0.2} - \frac{f_{1.0} - f_{0.2}}{E_{0.2}} \right) \times \left(\frac{f - f_{0.2}}{f_{1.0} - f_{0.2}} \right)^{n'} + \varepsilon_{0.2} \quad (4)$$

where, $\varepsilon_{0.2}$ and $\varepsilon_{1.0}$ are the total strains at $f_{0.2}$ and $f_{1.0}$, respectively, and n' is a strain-hardening exponent, determined using $f_{0.2}$ and $f_{1.0}$. Note that $\varepsilon_{1.0} - \varepsilon_{0.2} = 0.008$. Equation 4 gave excellent results, in both tension and compression, up to tensile strains of

about 10% and compressive strains of about 2%, since the compression coupons were loaded up to about 2% strains. Although point $f_{1.0}$ was chosen as a calibration point, it can be easily shown that Equation 4 does not pass through this point, however, the associated errors are negligible. To ensure that the curve passes through this point, Gardner and Ashraf (Gardner and Ashraf,2006) modified Equation 4 to give Equation 5.

$$\varepsilon = \frac{(f - f_{0.2})}{E_{0.2}} + \left[0.008 - (f_{1.0} - f_{0.2}) \left(\frac{1}{E_0} - \frac{1}{E_{0.2}} \right) \right] \times \left(\frac{f - f_{0.2}}{f_{1.0} - f_{0.2}} \right)^{n'} + \varepsilon_{0.2} \quad (5)$$

4. Conclusions

This review has shown that there has been a lot of effort to develop models that can predict structural elements, which undergo significant straining before reaching their ultimate capacity. Among these models, Gardner and Ashraf (Gardner and Ashraf,2006)'s modified model seems to be the most comprehensive model.

5. References

- Gardner, L., and Nethercot, D. A., 2004. "Experiments on stainless steel hollow sections. Part 1: Material and cross-sectional behaviour." *J. Constr. Steel Res.*, 60, 1291-1318.
- Gardner L, Ashraf M., 2006. Structural design for non-linear metallic materials. *Eng Struct*,28(6):925-36.
- Hill, H.N.,February 1944. Determination of Stress-Strain Relations from Offset Yield Strength Values, NACA Technical Note 927.
- Macdonald,M.,Rhodes,J.,Taylor, G. T.,2000. "Mechanical properties of stainless steel lipped channels." *Proc.*, 15th International Specialty Conf. on Cold-Formed Steel Structures, R. A. LaBoube and W. W. Yu, eds., St. Louis, Univ. of Missouri, Rolla, Mo., 673-686.
- Mirambell E, Real E.,2000. On the calculation of deflections in structural stainless steel beams: an experimental and numerical investigation, *Journal Constructional Steel Research*,54:109-133.
- Olsson A.,2001. Stainless steel plasticity—material modelling and structural applications. PhD thesis, Department of Civil and Mining Engineering, Lulea° University of Technology, Sweden.
- Quach W.M. , J.G Teng, K. F. Chung,2008. Three-stage full-range stress-strain model for stainless steels. *Journal of Structural Engineering*, ASCE 134,1518-27.
- Rasmussen KJR.,2003. Full-range stress-strain curves for stainless steel alloys, *Journal of Constructional Steel Research* 2003;59:47-61.
- Rasmussen, K. J. R., Burns, T., Bezkorovainy, P. and Bambach, M. R.,2003. "Numerical modelling of stainless steel plates in compression." *J. Constr. Steel Res.*, 59, 1345-1362.