

Time-invariant plastic deformation of ST 60 Mn: prediction models and design criteria

M. U. Onuu¹

ABSTRACT

Time-invariant plastic deformation of Steel, ST 60 Mn, locally produced by the Delta Steel complex, Aladja, Delta State, Nigeria, has been studied using a tensometer as the main instrument and regression as the tool of analysis. Empirical equations relating some design parameters and the relevant parameters pertaining to the steel under uniaxial tension have been proposed with a known factor of safety. This is necessary for the predication and formulation of design criteria. The results are justified upon testing the significance of the regression models.

Keywords: Plastic deformation, prediction models, design criteria, factor of safety.

INTRODUCTION

A properly designed machine member should operate within the elastic range of stresses. This is because beyond this range failure may occur either by plastic instability or gross plastic deformation. Thus, much skill of the structural engineer lies in recognizing that there are these failure modes in the plastic regime and in guarding against them in his design. This is necessary because the fundamental requirement for any engineering structure is that it should not fail in service. Damage mechanics in Physics of reliability and failure is a useful tool in solving problems of deformation in structures and machine members in design.

Apart from the determination of some properties and physical constants of a steel test-piece, the aim of a mechanical test may also be to establish some empirical relationships between some parameters of the test-piece. These properties and physical constants determine the use to which the steel may be put. This investigation which involves prediction and design criteria for this high strength steel of low ductility (Onuu and Adjepong, 1992; 1994 and Onuu, 2000) often used in construction and/or as a machine member is very necessary. The creep properties of this steel at intermediate temperatures and stresses have also been investigated (Onuu and Adjepong, 1998 and Onuu *et al.*, 1999).

The objective of this investigation is to develop empirical relationships between relevant parameters pertaining to the steel, ST 60 Mn, locally produced at Aladja, Delta State in the Federal Republic of Nigeria, under uniaxial tension and operating within the plastic regime and laboratory atmosphere of 28 °C.

PLASTIC THEORY AND PLASTIC BEHAVIOUR

The task of plastic theory is twofold: first to set up relationships between stress and strain which describe adequately the observed plastic deformation of metals, and second to develop techniques for using these relationships in the study of mechanics of metal forming processes, and the analysis and design of structures.

A number of formulae for the calculation of rupture stress, design stress, maximum percentage elongation and maximum strain have been proposed (Buxton and Burrows, 1951; Burrows *et al.* 1954, and Taira and Othani, 1971). The nature of these formulae depends mainly on the material used and stress distribution. The von Mises criterion has been accepted to define the effective stress, effective strain and the changes in effective stress namely:

$$\sigma^* = \frac{1}{2} [(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{1/2} \quad \dots (1)$$

$$\epsilon^* = \frac{\sqrt{2}}{3} [(\epsilon_1 - \epsilon_2)^2 + (\epsilon_2 - \epsilon_3)^2 + (\epsilon_3 - \epsilon_1)^2]^{1/2} \quad \dots (2)$$

$$\text{and } \Delta \epsilon^* = \frac{\sqrt{2}}{3} [(\Delta \epsilon_1 - \Delta \epsilon_2)^2 + (\Delta \epsilon_2 - \Delta \epsilon_3)^2 + (\Delta \epsilon_3 - \Delta \epsilon_1)^2]^{1/2} \quad \dots (3)$$

where: $\sigma_1, \sigma_2, \sigma_3$ and $\epsilon_1, \epsilon_2, \epsilon_3$ are the principal stresses and strains respectively with $\Delta \epsilon_1, \Delta \epsilon_2$ and $\Delta \epsilon_3$ as the corresponding changes in principal strains. For plastic flow under uniaxial tension

σ^* is the tensile stress where; $\sigma^* = \sigma_1$ when $\sigma_2 = \sigma_3 = 0$

$$\epsilon^* = \epsilon_1 \text{ when } \epsilon_2 = \epsilon_3 = -\frac{1}{2} \epsilon_1.$$

In design theory involving uniaxial stress, the effective stress, σ^* , can be taken as the yield stress, σ_Y .

These equations are only applicable if the elastic strains are small

compared with the plastic or creep strains. Another is the Levy-von Mises flow rule which is concerned with the direction of shape change and in its incremental flow form. It may be stated in the following form (Clarke and Barnes, 1971):

$$\frac{\sigma_1 - \sigma_2}{\Delta \varepsilon_1 - \Delta \varepsilon_2} = \frac{\sigma_2 - \sigma_3}{\Delta \varepsilon_2 - \Delta \varepsilon_3} = \frac{\sigma_3 - \sigma_1}{\Delta \varepsilon_3 - \Delta \varepsilon_1} \quad \dots (4)$$

In order to determine completely the actual values of the difference between strain increments in the principal directions, a further condition is required. This is the constant volume condition which is practically the case with plastic flow having negligible elastic strains,

$$\Delta \varepsilon_1 + \Delta \varepsilon_2 + \Delta \varepsilon_3 = 0 \quad \dots (5)$$

Simultaneous use of these conditions is assured by calculating strain increments using the following expressions:

$$\begin{aligned} \Delta \varepsilon_1 &= \frac{\Delta \varepsilon^*}{2\sigma^*} (2\sigma_1 - \sigma_2 - \sigma_3) \\ \Delta \varepsilon_2 &= \frac{\Delta \varepsilon^*}{2\sigma^*} (2\sigma_2 - \sigma_1 - \sigma_3) \end{aligned} \quad \dots (6)$$

$$\text{and } \Delta \varepsilon_3 = \frac{\Delta \varepsilon^*}{2\sigma^*} (2\sigma_3 - \sigma_2 - \sigma_1).$$

There is also the Tresca condition (Calladine, 1969):

$$|\sigma_1 - \sigma_2|, |\sigma_2 - \sigma_3|, |\sigma_3 - \sigma_1| = \sigma^* \quad \dots (7)$$

Thus, while Mises condition is related to the R.M.S. values of the principal stress differences, the Tresca condition concerns only the largest absolute values. In uniaxial tension, if W_f is the failure load, then the failure stress, σ_f , is, to a close approximation, given by

$$\sigma_f = \frac{W_f}{a_o} \quad \dots (8)$$

where a_o is the original cross-sectional area of the test piece to be used in design.

In engineering design it is usual to use a factor of safety in the calculation of the design stress, σ_d . This is done by noting the margin between operating stress levels and failure strengths. This margin must be decided with due regards for the many uncertainties associated with material properties, loading configurations; accuracy of assumed physical and mathematical models relating load, material, failure response, and other factors. The factor of safety, n , is related to failure stress and design stress by the expression:

$$\sigma_f = n\sigma_d \quad \dots (9)$$

$$\text{i.e. } n = \frac{\sigma_f}{\sigma_d} \quad \dots (10)$$

An average for the factor of safety is 2 (Collins, 1981). If the factor of safety is too small, the machine part will have an unduly high probability of failure. If it is picked too large the weight, size and cost may make the design impossible.

The current gauge length of a specimen with an original length, l_o , is given by: $l = l_o(1 + e)$... (11)

where; e is the engineer's strain. The true or logarithmic strain is:

$$\varepsilon = \int_{l_o}^l \frac{dl}{l} = \ln \frac{l}{l_o} = \ln(1 + e) \quad \dots (12)$$

$$\text{Under constant volume condition, } a_o l_o = al \quad \dots (13)$$

where a is the current cross-sectional areas.

$$\text{Thus, } \frac{a_o}{a} = \frac{l}{l_o} = (1 + e) \quad \dots (14)$$

$$\text{The true stress, } s, \text{ will be } s = \frac{P}{a} \quad \dots (15)$$

where P is the load.

$$\text{Therefore, } s = \frac{a_o}{a} \sigma = (1 + e)\sigma \quad \dots (16)$$

Absolute values of σ and ε have been plotted (Calladine, 1969) so that the tension and compression curves are directly comparable. The two curves are close to each other, and they indicate that plastic behaviour is remarkably similar in tension and compression, provided due allowance is made for changes in geometry.

EXPERIMENTAL DETAILS

Materials

The specimens tested were locally produced steels designated ST 60 Mn in DIN1611 of the West German Norm for commercial construction steels. The steel, which has the product code B/120/006, was produced by combined Midrex reduction process (electric arc furnace route). The liquid steel was cast into billets, which were hot-rolled into 25mm-diameter rods. The chemical composition of the steel grade obtained with Emissions Spectrometer PV 8350 is given in Table 1.

Sample preparation

The specimens which were subjected to uniaxial tensile loading were machined from the as-received bar of 25.00 ± 0.01 mm diameter to 4.00 ± 0.01 mm ready for pre-straining that was accompanied by plastic flow. Pre-straining gives a material a distinct internal grain effect along one direction, say, rolling (Pritchard, 1970). It enables the material to withstand further change in structure or shape until a desired result is achieved. Pre-straining was carried out at the temperature of 28 °C; which is far below the lower critical temperature for steel (just above 700°C). Below this lower critical temperature, the pearlitic structure of steel is maintained (Chapman, 1978).

Two stages were involved which resulted in reduction of diameter, namely the preliminary and final stages. The preliminary stage involved a step-by-step reduction of diameter of the rod using two machine rollers one consisting of the driven gear and the other the

Table 1. Chemical composition of ST 60 Mn steel grade used in the investigation.

Steel grade	Condition	Chemical composition (Wt. %)							
		C	S	Mn	P (max)	Cu (max.)	Cr(max.)	N(max.)	Sn
ST 60 Mn	Hot-rolled	0.35-0.42	0.20-0.30	0.90-1.20	0.04	0.25	0.10	0.11	0.05

driver gear. Final stage (process) consisted in pulling the product of the initial stage through a hard and highly polished die. A machine with low efficiency was chosen to ensure that the effect of cold-working was negligible. Because of the low carbon content of the steel it would gain little or no hardness unlike those in excess of 0.8% C (Pritchard, 1970). The samples were reduced to various diameters of 3.00 ± 0.01 , 2.50 ± 0.01 , 2.00 ± 0.01 and 1.53 ± 0.01 mm.

Testing

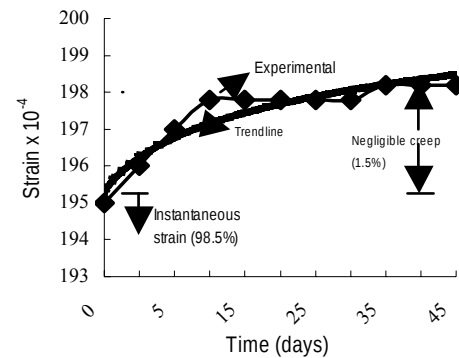
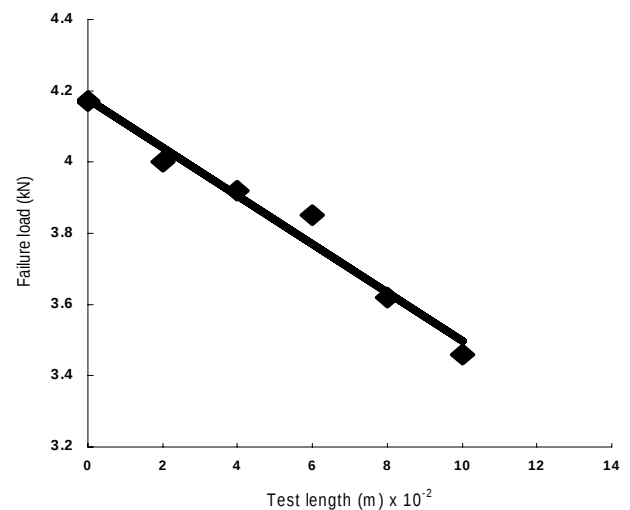
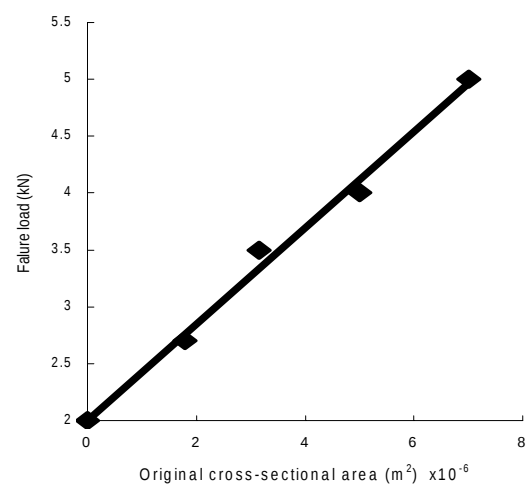
The specimen was loaded beyond the yield stress and room temperature creep test was carried out for 45 days (1,176 hrs). This was to find out whether plastic deformation was time-dependent at this temperature. Tensile testing of the specimens was carried out at 28°C under a laboratory atmosphere by means of the Monsanto tensometer of 20 kN maximum capacity. The test was continued until the specimen broke. The above procedure was repeated for a number of specimens of known test length and cross-sectional area. When the test length was not varied, it was fixed at 2.0 cm.

All measurements were made using a traveling microscope. The gear ratio on the drum drive of the tensometer was set at 16:1 corresponding to magnification of elongation by 16.

Analysis, results and discussion.

In all the measurements, elongation corresponding to each incremental load was calculated from the special tensometer graph.

Figure 1 shows a plot of the room temperature creep of the specimen for the test duration of 45 days (1,176 hrs). This produced instantaneous strain of 98.50% of the deformation and only 1.50% representing creep. Plastic deformation was there found to be mainly time-independent. In Figures 2 and 3, the failure stress, σ_f , is plotted against the test-(or design) length, l_o and original cross-sectional area, A_o respectively. The maximum percentage elongation, $\%E_{\max.}$, and maximum strain, $\epsilon_{\max.}$, are plotted against the test-length and original cross-sectional area as shown in Figs 4 and 5 respectively. Empirical relationships between some design parameters and relevant parameters pertaining to the steel have been developed. Significant tests at 5% level were carried out for these relationships using F-tables and there were all found to be significant at that level. Regression coefficients for the models were found to lie between 0.9680 and 0.9958 which shows that the data fit the points very well in each of them. These results are summarized in Table 2. The empirical relationships between design stress and test length; design

**Fig.1. Room temperature creep at constant stress of $8.35 \times 10^9 \text{ Nm}^{-2}$** **Fig.2. Failure load vs. test length****Fig. 3. Failure load versus original cross-sectional area**

stress and original cross-sectional area, were found to be linear while those between maximum percentage elongation and test-length, and maximum strain and cross-sectional area were best described by a

Table 2. Summary of results*

S/No.	Design parameters being regressed on some parameters of the steel	Coefficients		R	Significant test at 5% level
		p	q		
1	σ_d on l_o , $a_o = \text{const.}$	$\frac{-0.068}{na_o}$	$\frac{4.1767}{na_o}$	0.9837	Significant
2	σ_d on a_o , $l_o = \text{const.}$	$\frac{0.4235}{n}$	$\frac{2.0034}{na_o}$	0.9958	Significant
3	$\%E_{\max.}$ on l_o , $a_o = \text{const.}$	9825.5	-1.1417	0.9722	Significant
4	$\varepsilon_{\max.}$ on a_o , $l_o = \text{const.}$	10.014	0.6476	0.9680	Significant

* Established models are $y = px + q$ for S/Nos. 1 and 2 and $y = px^q$ for 3 and 4.

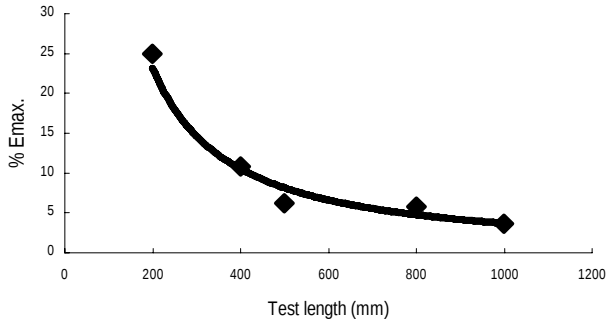


Fig. 4. Percent maximum elongation versus test length for same diameter of 2.25mm

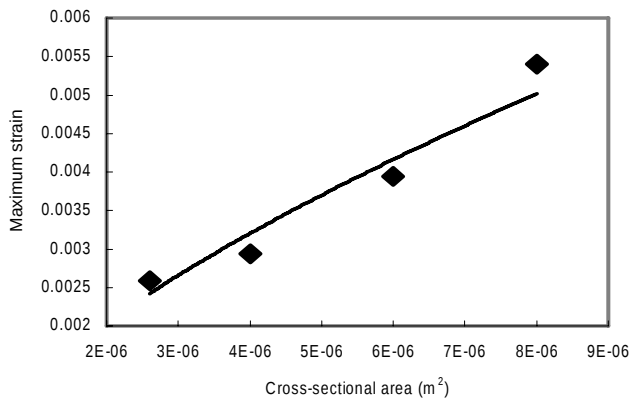


Fig. 5. Maximum strain versus cross-sectional area for text –length of 20 mm

power law. From the results designers and structural engineers who intend to use the construction steel in design and construction work

CONCLUSION

With only 1.50% of the total deformation representing creep and 98.50% of it accounting for instantaneous strain, the 45 day-room temperature creep test clearly shows that plastic flow of this material is time-invariant at this temperature. Plastic failure can be predicted when using ST 60 Mn in design by judicious choice of dimensions and sizes in relation to some critical design parameters in accordance with the empirical models that have been proposed.

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