Influence of Prestraining on Tangent Modulus of Tubular Struts

Lewis Schmidt[1] (Prof. of Civil Eng.) & Seyed M.R.Mortazavi[2] (B.Sc.,M.E.,Ph.D.)

Abstract

Strain reversal in the inelastic range may cause a dramatic drop in the tangent modulus for mild steel struts. Other material properties also affect the tangent modulus. Consequently the influence of several of these properties is examined for an electric-resistance welded steel tube. The variables chosen are: (1) Strain hardening caused by varying the amount of tensile prestrain; (2) strain aging; (3) and the Bauschinger effect, for a specific steel type. The results of 39 stub column tests on semi-killed steel specimens show that tensile prestrain reduces the tangent modulus compared with that found for the as-received tube, but strain aging is seen to be significant in reducing this loss in value. The variations obtained for the tangent modulus are illustrated. The variations are given as functions of the amount of tensile prestrain and whether the steel is fully aged or non-aged. The importance of knowledge of prior strain history of a material is highlighted.

Keywords

Tangent modulus; Prestraining; Bauschinger; Strain Hardening; Strain aging; Struts; Tube.

Definitions of Strain Hardening, Strain Aging and the Bauschinger Effect

Strain hardening is a term used to define the increase in strength with increasing strain as plastic deformation or flow occurs beyond the yield point [1]. Fig.1 illustrates this phenomenon for a mild steel. If, after strain hardening occurs in a test, unloading takes place (path cc' in Fig.1) and then reloading follows, the path taken depends on the time since unloading, and any temperature changes which may have been applied. The strength increase (CD in Fig.1) is a measure of strain aging.

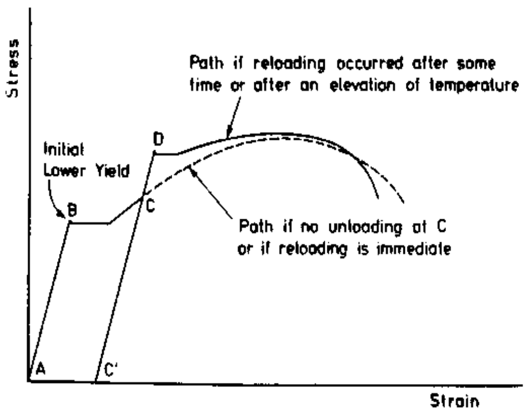

Fig.1 Stress-Strain Curves for Mild Steel.

Whenever the direction of strain is reversed there may be a significant loss of yield strength, compared with the original value. This loss of yield strength is normally referred to as the Bauschinger effect. Bauschinger first reported that after plastic deformation of a metallic material the elastic limit was higher for subsequent loading in the same direction than for loading in the reverse direction [2].

The significant aspects of the three phenomena mentioned so far are illustrated in Fig.2. Path ABCD includes the strain hardening effect; path ABCDQ includes strain hardening and the Bauschinger effect; path ABCDEFGHR includes strain hardening, strain aging, and the Bauschinger effect. Curves labeled C', D' and H' are reflected reverse images of the corresponding parts of the virgin curve, and are included as reference curves. The base stress against which the Bauschinger effect may be measured depends on the previous stress and temperature history of the material, which may also include strain hardening and strain aging.

1- University of Wollongong, Australia

2- Senior Lecturer of Civil Eng.

Shahid Rajaee Teacher Training University, Tehran-Iran

mortazavimr@yahoo.com

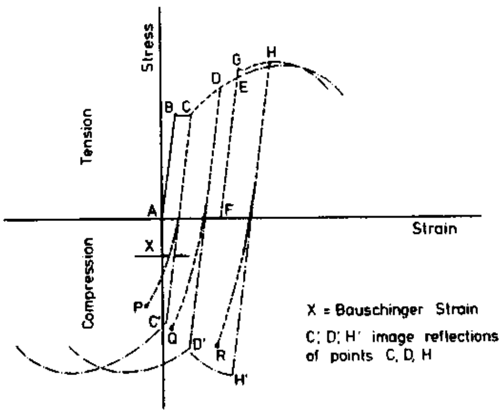

Fig. 2 Stress-Strain Curves Illustrating Strain Hardening, Strain Aging and the Bauschinger Effect.

Typical manufactured tubes are classified according to the forming process and the heating conditions used in manufacture as follows[3]:
1- Electric resistance welding (ERW): A strip is cold-formed by rolls into a circular shape, and the edges are heated to welding temperature by resistance to the flow of an electric current. This process is referred to as " cold-formed and electric resistance welded ".
2- Cold-formed stress relieved: If heat is applied after forming by method 1, the product is referred to as " cold-formed stress relieved " tube.
The manufacturing methods of circular tubes may vary from one producer to the next, depending on equipment, technical preference, and the intended applications.
In the manufacturing process of cold-formed and electric resistance welded tube, the material passes through an additional variety of processes subsequent to those used in the production of the parent material. These processes may enhance certain properties, but may reduce others. The application of cold work increases the tensile yield strength but reduces the ductility of mild steel, while the thermal treatment of annealing lowers the yield strength but improves the ductility of a previously cold worked member [4].
One way in which circular tubular members are manufactured is by a process that cold straightens the flat strip from preformed coils, passes the strip through roll formers, and then welds the edges together by an electric-resistance welding process (method No.1). This process is followed by further roll straightening to overcome the distortion caused by the welding operation. As a consequence of these steps in the production process, residual stress patterns are caused by plastic deformation in both the longitudinal and circumferential directions, and occur together with the welding residual stresses[5-7].
The process of cold straightening of the coil and roll forming into a circular section causes the steel to be strained well into the plastic range; strain aging will take place slowly or quickly depending on the temperature and the type of steel used, whether fully-killed, semi-killed or rimmed. Fully-killed steels display virtually no strain aging capacity, whereas rimming steels offer significant strain aging. Semi-killed steels have an intermediate tendency for strain aging and fall between fully-killed and rimmed steels in this regard. Owing to the welding process occurring after these operations, strain aging probably takes place almost immediately, as the temperature of the material rises significantly. However, additional plastic straining occurs in the final roll straightening operation and further strain aging is probably small. Depending on the type of mild steel used in the tube production process, an enhanced yield point may result, offsetting to some extent the effects of the residual stresses[8-10]. For example, rimmed steel is more sensitive to strain aging than a fully killed steel in which no strain aging is displayed. The purpose of this paper is to show the influence of strain hardening, strain aging, the Bauschinger effect and residual stresses on the tangent modulus (E_t) values of stub column specimens cut from prestrained electric resistance welded (ERW) mild steel tubes.

Experimental Tests - ERW Tubes

Tests for material behaviour in tension and compression were carried out to furnish basic data in the elastic and inelastic ranges, including the influence of strain hardening, strain aging and the Bauschinger effect.

Description of Material and Specimens

The material used in the tests was a hot-rolled semi-killed steel. The tubular cross-section chosen for study had an outside diameter 63mm with wall thickness 2.5mm.
The tube was produced by cold-forming and seamed by the Electric Resistance Welding (ERW) process.
Tests for material behaviour in tension and compression were needed to furnish basic data in the elastic and inelastic ranges under forward and reverse loading.
Tensile specimens were prepared. These were tubes of 600mm length with 12mm thick end plates to provide grips for the testing machine.
Compressive specimens were prepared. The compressive specimens were tubes of 201mm length (3.2 times outside diameter) and are referred to as stub columns. The specimens were short enough to prevent any possibility of overall instability (column buckling) influencing results. The ends of the stub columns were machined to provide good contact with the plates of the testing machine.

Instrumentation

All of the material tests were carried out, using a 50 tonne digital servo-hydraulic testing system (Instron machine) with controlled rates of ram travel.

Tensile tests were performed, and a load-deflection diagram was plotted. To check the elastic modulus, and permit other more detailed calculations, stub column tests were performed. An extensometer of length 100mm was mounted centrally with respect to the length of each test specimen (see Fig.3), and the specimen contraction was measured with two linear variable displacement transducers (LVDT). A Hewlett Packard X-Y plotter allowed load-deflection plots to be obtained. Two readings were taken at locations 180 degrees apart in plan around the longitudinal axis of the tube, and the average of two readings used to obtain the final contraction.

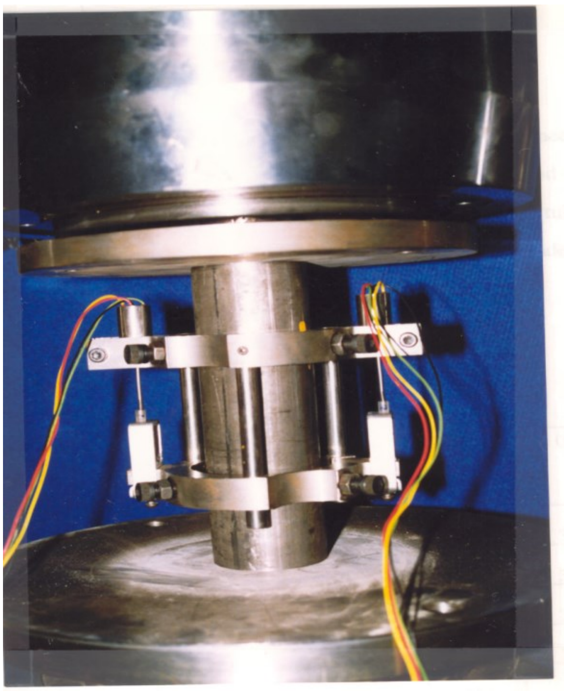

Fig.3 Stub Column Test, Instron Machine and Extensometer.

Material Tests

Tests on As-Received Tensile and Compressive Tubes

Tests for material behaviour in tension and compression were needed to furnish basic data in the elastic and inelastic ranges under forward and reverse loading. The details of the tensile and stub column tests on as-received tubes are summarized and listed in Tables 1 and 2 in which reference is made to the significant levels of the idealised stress-strain curves of Fig.4.

Table 1 Tensile Test Results

Test No.	Max.Load M (kN)	Yield Load A (kN)	$\frac{M}{A}$,(SHR)	$\frac{M-A}{A}$ %	σ_y (MPa)	σ_u (MPa)
I1	169	149	1.134	13.4	311	353
I2	181	160	1.137	13.1	334	378
I3	172	152	1.131	13.1	317	359
I4	180	161	1.118	11.8	336	376
I5	181	162	1.117	11.7	338	378

SHR = Strain Hardening Ratio, σ_y =Yield Stress, σ_u = Ultimate Stress

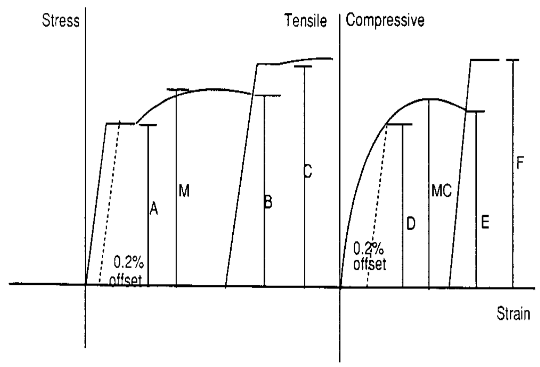

Fig.4 Idealised Tensile and Compressive Stress-Strain Curves.

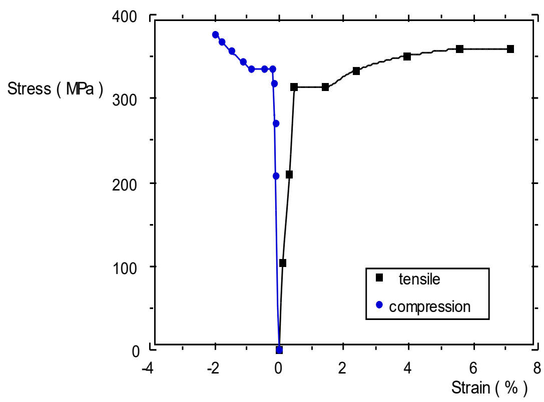

Fig.5 Typical Stress-Strain Curves for As-Received Materials.

Typical stress-strain curves in tension and in compression for as-received material are shown in Fig.5 . The material had a defined yield point and the average yield value for all five tensile tubes was 328 MPa, and for all seven stub column tests was 331MPa. The average value of the modulus of elasticity (E) was 213 GPa.

Table 2 Stub Column Tests on As-Received ERW Tubes (Tubes I1-I4 recompressed).

No.	Max.Load M(kN)	Yield Load A(kN)	%Strain before unloading	B (kN)	Cond.	C (kN)	$\frac{C-B}{B}$ (%)	$\frac{M-A}{A}$ (%)	E (GPa)
I1	175	156	1.56	174	Aged*	183	5.1	12.1	
I2	178	157.75	0.84	166	Aged*	185	11.4	12.8	214
I3	180	158	1.96	180	Aged**	192.6	7	13.9	
I4	180	158	1.90	180	F.A.	194	7.7	13.9	
I5	180	158	2.00	180				13.9	219
I6	180	159							
I7		156							206

* Aged for 20 minutes at 100 ^{o} C
** Aged for 154 days at ambient temp. (25 ^{o}C)
FA= Fully aged for 2 hours at 100 ^{o}C
Cond.= Condition
E = Modulus of Elasticity

The stub column tests continued until local buckling occurred at a position along the stub column specimen. Therefore, the tests directly reflected the influence of both the residual stress distribution and the variation of yield stress on column strength.

Stub Column Tests on Prestrained ERW Tube and Tangent Modulus E_t

In addition to these tensile and compressive tests on as-received tube, tests were required to ascertain the influence of strain aging and strain hardening with respect to the Bauschinger effect. For this purpose, the tubes were prestrained in tension to a defined percentage elongation.

The stub column test specimens were performed on 201mm length cut from the prestrained tube in tension to 0.78% and 1.57%, respectively. To determine the effect of aging, specimens C and D (Table 3) were initially prestrained to the defined percentages and then different aging treatments were applied, before loading in the opposite direction (compression). Specimens C and D were prestrained in tension to 0.78% and 1.57% respectively, and were followed by fully aging ('full' aging was determined to be 2 hours at 100 ^{0} C), except specimen D3 which was aged for 133 days at ambient temperature. Specimens C and D were cut into three 201mm length cylindrical specimens and then tested in compression. Specimens A and B (Table 3) were prestrained in tension to 0.78% and 1.57% respectively, and tested in compression. Table 3 indicates the results for prestrained and aged ERW tube from comparative tests devised to show the variations in the strength of the material under different conditions.

The stress-strain curves of the stub column tests are presented in Figs.6 to 10 for as received tubes, 0.78% prestrained in tension and unaged tubes, 1.57% prestrained in tension and unaged tubes, 0.78% prestrained and fully aged tubes, 1.57% prestrained and fully aged tubes, respectively. The combined stress-strain curves of the stub column tests for all conditions are presented in Fig.11.

The Bauschinger effect can be seen on load reversal following plastic tensile prestraining. It is evident by the absence of a definite yield point and the rounding of the stress-strain curve from stress levels lower than the original virgin yield stress[11]. This change depends on the relative influence of strain hardening and strain aging on the tests.

Table 3 Stub Column Tests on Prestrained ERW Tube.

No.	A (kN)	%Strain before unloading	B (kN)	Cond.	D (kN)	$\frac{D-A}{A}$ (%)	Mc (kN)	E (kN)	Cond.	F (kN)	$\frac{F-E}{E}$ (%)	$\frac{Mc-D}{D}$ (%)
A	161	0.78	161	AR								
A1				PS+NA	146	-9.3	174	174				19.1
A2				PS+NA	144	-11	172	172				19.4
B	172	1.57	173	AR								
B1				PS+NA	139.6	-18.8	183.9	183.9				31
B2				PS+NA	139.6	-18.8	186.9	186.9				33
C	160	0.78	160	AR								
C1				PS+FA	154.5	-3.4	176	176				13.9
C2				PS+FA	153	-4.3	174	174	PS+FA	197.9	13.7	13.7
C3				PS+FA	157	-1.9	178	178	PS+FA	196	10.1	13.3
D	170	1.57	170	AR								
D1				PS+FA	150.9	-11.2	176.6	176.6	PS+FA	190.2	7.7	16.9
D2				PS+FA	150.9	-11.2	176	176	PS+FA	196.9	11.8	16.5
D3				PS+A*	148.7	-12.5	176.8	176.8	PS+FA	191.3	8.2	18.8

AR = As-Received, PS = Prestrained in tension, NA = No Strain Aging
FA = Fully Strain Aged (two hours at 100 $^{\circ}$C), Cond. = Condition
The symbols (A, B, D, Mc, E, F) used in this table defined in Fig.4.
* Aged for 133 days at ambient temperature (25 $^{\circ}$C)

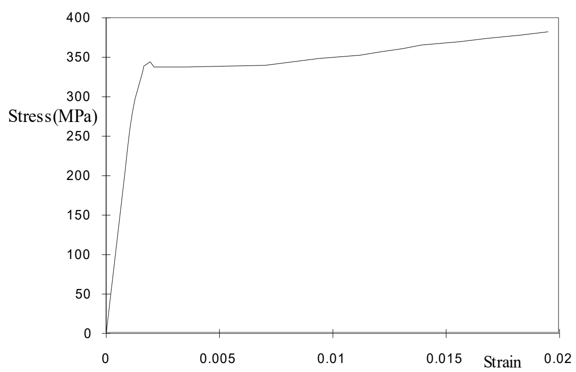

Fig.6 Stub-Column Test, As-Received Tubes.

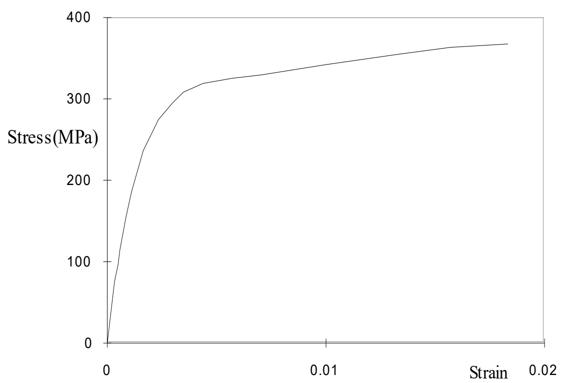

Fig.7 Stub-Column Test, 0.78% Prestrained, As-Received Unaged.

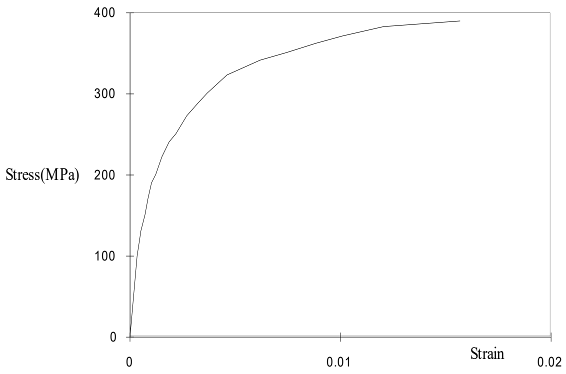

Fig.8 Stub-Column Test, 1.57%Prestrained, As-Received Unaged.

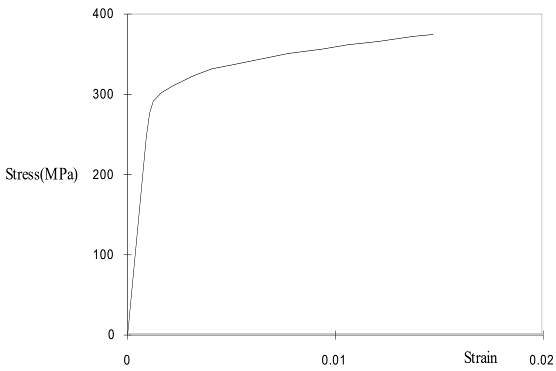

Fig.9 Stub-Column Test, 0.78%Prestrained, Fully-Aged.

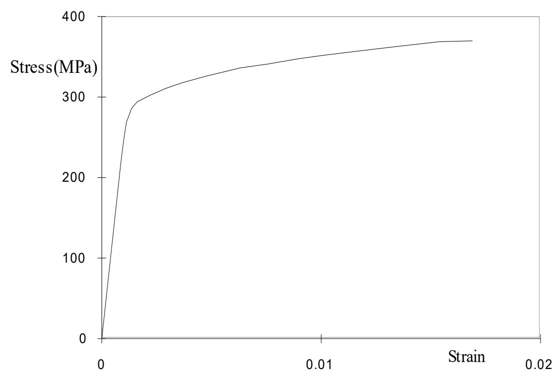

Fig.10 Stub-Column Test, 1.57%Prestrained, Fully-Aged.

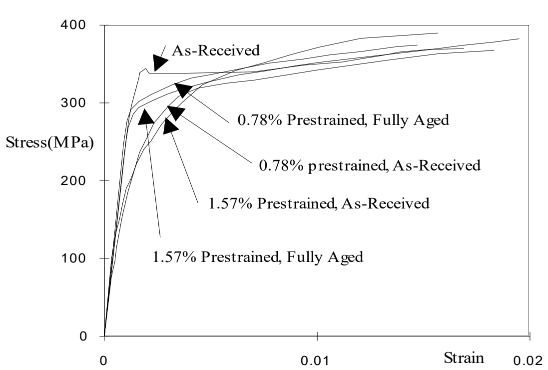

Fig.11 Stub-Column Test Results Under Different Conditions.

From the stress-strain curves given in Figs.6 to 10, values of the tangent modulus (E_t) were obtained graphically for given values of stresses. In this series of tests five classes of behaviour were observed, depending on the tensile prestrain and aging treatment. The variation of tangent modulus with stress was found to be significantly different for each class of test, and is shown in combination in Fig.12.

The results show that aging has a significant effect on the tangent modulus of elasticity. The 0.78% and 1.57% prestrained and fully aged curves are well above the 0.78% and 1.57% prestrained and unaged curves in the same range of stress as shown in Fig.12.

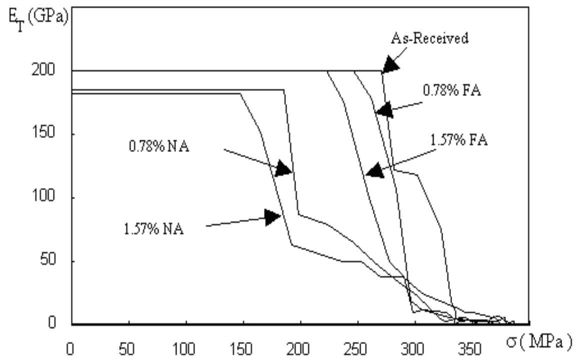

Fig.12 Tangent Modulus vs Stress, ERW Tube Under Different Conditions

Tests on As-Received Stress-Relief-Annealed and Prestrained Stress-Relief-Annealed ERW Tube

Stress-relief-annealing (SRA) treatment was carried out by means of a natural gas-fired furnace. The particular annealing temperature and length of heating time applied, depends on the anticipated use of the final product. The tubular specimens were stress-relief-annealed at 620 ^{o}C for 30 minutes. This process was adopted so as to relieve the residual stresses set up during the tube manufacturing process.

Eleven stub column tests, which were stress-relief-annealed, were tested to furnish basic data in the elastic and inelastic ranges. Five were as-received and stress-relief-annealed (SRA), three were 0.78% prestrained and stress-relief-annealed (0.78% SRA), three were 1.57% prestrained and stress-relief-annealed (1.57% SRA).

Comparing the stress-strain curve results to the as-received SRA, 0.78% SRA, 1.57% SRA stub columns, the very well-defined yield plateau of the stress-relief-annealed stub column tests indicated that residual stresses set up during the manufacturing process of the tubular section existed (Fig.13). The initial tensile prestrain of the stress-relief-annealed tube had no effect on the stress-strain curves and the stress-relief-annealing process lowered the yield stress of stub column specimens. The tubes were initially prestrained in tension and then stress-relief-annealed and tested in compression.

The variation of Tangent Modulus (E_t) against stress (σ) under all of the stress-relief-annealed conditions is shown in Fig.15. No significant changes in Tangent Modulus was observed due to prestraining.

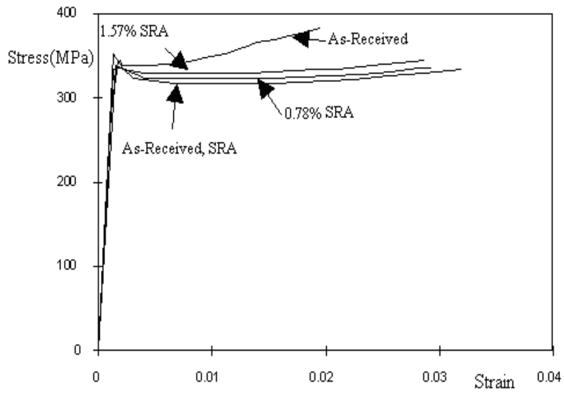

Fig.13 Stub-Column Test Results, As-Received and All Stress-Relief-Annealing Conditions

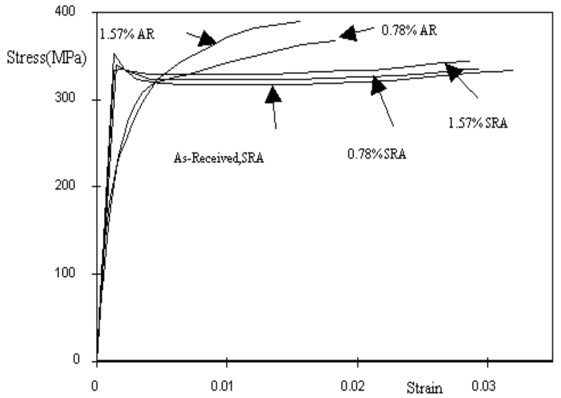

Fig.14 Stub-Column Test Results, Stress-Relief-Annealed Comditions and 1.57% and 78% Prestrained, As-Received

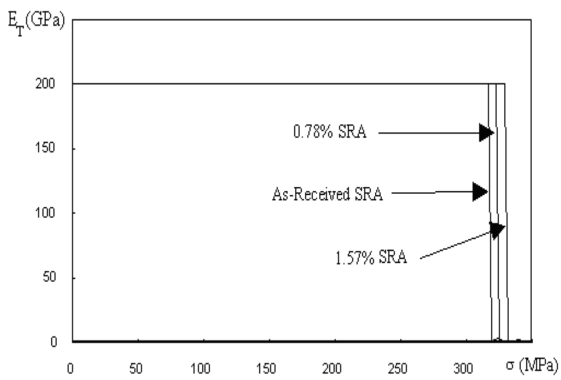

Fig.15 Tangent Modulus vs Stress, ERW Tube Under All Stree-Relief-Annealing Conditions

Comments and Conclusions

Several compressive tests were performed followed by strain aging and immediate reloading. Strain gains of 5-11% were observed following prestrains of 0.84 to 1.96%, after 154 days at ambient temperature aging and 20 minutes to 2 hours aging at 100 ^{o}C (Table2). Further tests were also carried out to check the influence of strain aging after load reversal from tension to compression, then further reload cycles were performed. Whenever additional plastic deformation (further reload cycles) was applied strain aging occurred. "Full" aging led to strength gains of approximately 8-14% after further reload cycles.

For the ERW tube used the strain hardening ratio was 1.13 (Table1). It was found the Bauschinger effect (loss of material strength or stiffness or both on load reversal) cannot be completely isolated from the increase of strength due to strain aging and strain hardening.

The Bauschinger effect (the reduction of yield stress) occurred in compression for all the tensile prestrained, unaged tubes, and the Bauschinger effect was interactive with both strain aging and strain hardening. Strain hardening of the ERW tube had relatively little influence on the Bauschinger loss, due to its low strain hardening capacity, having a strain hardening ratio of 1.13.

When aging occurred after prestraining in tension, over an extended time at ambient temperatures or was accelerated in an oven, the influence on the Bauschinger loss was clear. As the tensile prestrain increased from 0.78% to 1.57%, the compressive strength reduction increased from 8% to 11%, respectively (compared with the as-received ERW tube); under an unaged condition, and under a fully aged condition from 1.7% to 4%, respectively. Comparing the amount of the Bauschinger loss under the different conditions indicates that strain aging is a dominant factor in the experimental work represented herein.

The as-received and stress-relief-annealed tubes had the highest value for E_t. The larger the amount of tensile prestrain the lower the value of E_t for the prestrained tubes. The influence of strain aging is significant; fully aging furnishes higher values of E_t for given values of prestrains. No significant changes in Tangent Modulus was observed due to prestraining for stress-relief-annealed tubes.

In ultimate load calculations for struts, allowance need to be made for the reduced values for E_t under stress reversal.

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