EFFECT OF PRE-STRAIN ON THE PLASTICITY RESPONSE OF X65 PIPELINE STEEL

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Abstract- In many cases, pipelines are subjected to tensile pre-strain during its installation or service. In response to such pre-strained history, this present study focus on plasticity aspects due to pre-strain on the stress-strain relation between yield and ultimate point. Small scale tensile test experiment of API-5L-X65 pipeline steel was conducted in a sequence of loading-unloading-reloading process. The other associated data was discussed in the relation of pre-strain to the plastic strain and the relation of pre-strain to the remaining strain capacity and the remaining strain hardening. As the result, the plastic strain have linear function to its total pre-strain, and the remaining strain capacity and strain hardening capacity decrease with increasing of pre-strain. Meanwhile, in specific plasticity aspect due to pre-strain, stress-strain relation of the tested specimens under pre-strain effect can be simplified by linear equation.

Keywords- Pre-Strain, True Stress–True Strain, X65 Pipeline Steel, Flow Stress.

I. INTRODUCTION

Oil and gas steel pipelines naturally can be subjected to longitudinal extent during its installation or service. These conditions can arise when the pipeline crosses harsh environments such as permafrost region, landslides, etc. which could impose longitudinal plastic deformations to the pipeline. As plastic deformation is considered as non-reversible process where Hooke's law is no longer valid, it is useful to evaluate flow from beyond the yield up to the ultimate tensile strength. As the material starts to deform plastically when the yield surface is reached, further loading results the deformation in a constitutive model or power law relation. This plastic zone then becomes important because in strain-based approach, certain strain capacity need to be reviewed before causing excessive yielding. In regard to the above pre-deformation, a single pre-strain cycle is considered in this paper.

Detrimental effect of significant pre-strain and its effect specifically on fracture toughness has considered in [1] whereas several investigations have performed in recent decade in regard to the "macro" effect of pre-strain on stress-strain curve or relevant mechanical properties, e.g. [2] [3]-[5]. Pre-strain significantly affect the mechanical properties of steel, where yield strength and tensile strength increased with increasing tensile pre-strain, and the increasing rate of the yield strength was greater than that of the tensile strength [4].

It is well known the common model [7] to describe plastic zone in the basic equation as:

$$\sigma = K.\varepsilon^n \qquad (1)$$

Swift [6] modified the above equation in order to include the initial strain as:

$$\sigma = K(\varepsilon_0 + \varepsilon)^n \qquad (2)$$

where σ is the true stress, ε is true strain, ε_o is pre-strain constant, K is a strength coefficient (equal to the true stress at $\varepsilon = 1.0$), and n is the strain-hardening exponent.

In this study, stress-strain relation was evaluated by using Fernandes formula [5] in order to predict the true stress-strain path beyond the yield, up to the ultimate strength. Fernandes accommodated pre-strain history by using modified Swift's power law:

$$\sigma^* = k\left[F\left(\varepsilon_0 + \varepsilon_p\right) + \varepsilon^*\right]^n \qquad (3)$$

where σ^* and ε^* are the equivalent stress and strain in reloading step, respectively, and F is a parameter (assumed as linear) that depends on the strain path change. As shown in Fig. 1, the stress gap between the reloading curve and the reference curve vanishes with increasing strain. The reloading yield stress commonly defined as the back extra- polated stress (σ_{be}), is higher than the reference stress (σ_r), measured at the same equivalent strain on the curve without pre-strain, called the reference curve.

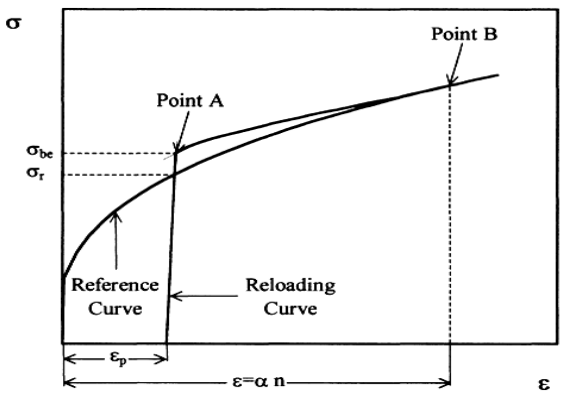


Fig. 1 Schematic representation of true stress-true strain curves in tension without pre-strain and after a pre-strain to ε_p [5].

By introducing a normalised yield stress $\frac{\sigma_{be}}{\sigma_r}$ (from reloading step) into Swift formula, modified flow

stress then be expressed as equation (4) [5], where for higher pre-strain value, it is assumed that strain distribution behavior will be depend on $\frac{\sigma_{be}}{\sigma_r}$ ratio.

$$\sigma^* = k\left[\left(\frac{\sigma_{be}}{\sigma_r}\right)^{\frac{1}{n}}(\varepsilon_0 + \varepsilon_p) + \frac{(\varepsilon_0+\alpha n) - \left(\frac{\sigma_{be}}{\sigma_r}\right)^{\frac{1}{n}}(\varepsilon_0+\varepsilon_p)}{(\alpha n-\varepsilon_p)}\,\varepsilon^*\right]^n \quad (4)$$

In this present study, the above equation was plotted against the strain and was compared to the experiment result.

II. EXPERIMENT

2.1 Specimen and Geometry

The specimens was cut in longitudinal direction from pipeline steel (API-5L-X65) which have 812.8mm diameter pipe and fabricated for final thickness 19,1mm. The chemical composition of the materials is given in Table 1.

Table 1. The chemical composition of the tested X65 pipeline steel (% mass).

C	Mn	Si	P	S	P	Al	Nb
0.083	1.568	0.224	0.02	0.005	0.02	0.03	0.05

V	Ti	Cr	Cu	W	Sn	Sb	Zr
0.048	0.13	0.03	0.023	0.005	0.002	0.011	0.001

Zn	Fe
0.001	Balance

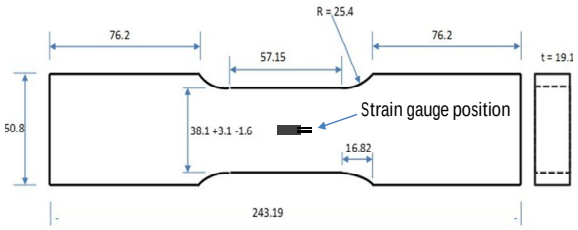


Fig. 2 Specimen dimensional (mm).

2.2 Pre-strain

Specimen was fabricated and tested in a loading-unloading step as per ASTM E8 [8] which were carried out on the universal testing machine having capacity 1000kN and the stretching rate was 0.02mm/second. A strain gauge is mounted in center position of the specimen as shown in Fig. 2 in order to provide strain data, thus provide the stress-strain curve result as shown in Fig. 3. From the plastic region of the curve, generated the strength coefficient K is 858MPa, strain hardening coefficient n is 0.098 and yield to tensile ratio Y/T is 0.82. After the pre-strain, specimen was reloaded to study the effect of pre-strain.

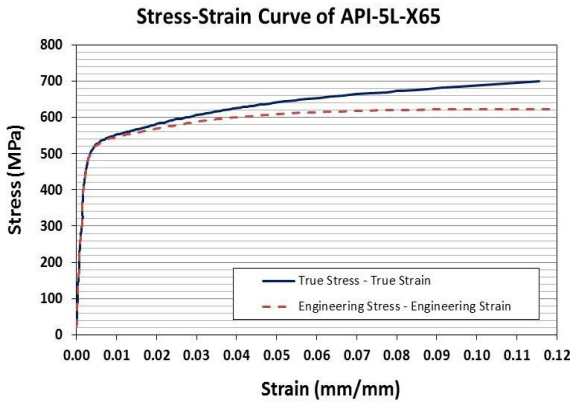


Fig. 3 Strain-strain data of tested steel up to ultimate tensile strength.

2.3 Tensile Test

Specimen was carried out in reloading step on the universal testing machine capacity 1000kN and the stretching rate was 0.02mm/second. A strain gauge is mounted again in center position of the specimen as shown in Fig. 4 in order to provide strain data.



Fig. 4 Position of strain gauge mounted on pre-strained specimen.

III. RESULT AND DISCUSSION

3.1 Permanent Set Effect

Accompanied permanent set of strain (plastic strain) after loading-unloading will affect the remaining strain capacity and the remaining strain hardening capacity during reloading. A completed loading-unloading sequence confirms a linear correlation between the pre-strain in terms of total strain ε_t and the permanent set of plastic strain ε_p:

$$\varepsilon_p = 0.9863\,\varepsilon_t - 0.0026 \quad (5)$$

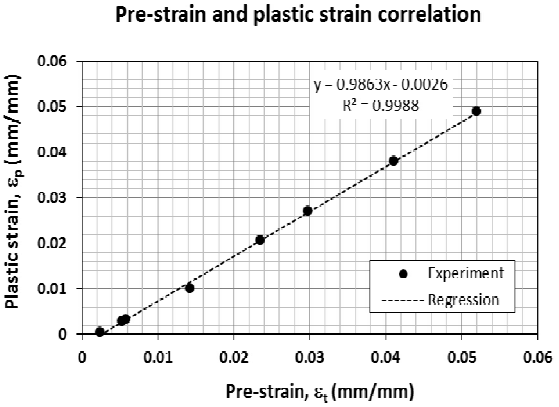


Fig. 5 Correlation between pre- strain (total strain) and plastic strain.

It is assumed that the failure occurs before excessive yielding therefore the remaining strain capacity then is defined as capacity of the strain during reloading up to strain on the ultimate tensile strength. As shown in Fig. 6, pre-strain decrease the remaining strain capacity with significant trend. It is shown that the loss of remaining tensile strain capacity was occurred quickly with the increasing several percent of pre-strain. This result support to previous study as reported in [9] in order to take into account the effect of pre-strain in engineering critical assessment of pipes during operation.

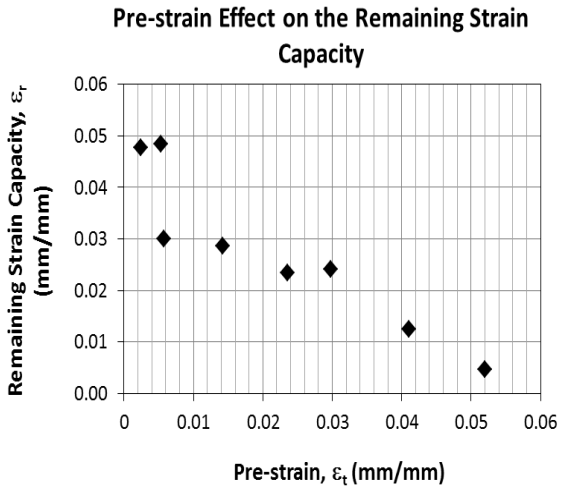


Fig. 6 Pre-strain effect on the remaining strain capacity

Pre-strain was reported to affect the strain hardening capacity. Fukuda [10] was revealed that and work hardening were dependent on the yield-to-tensile ratio (Y/T) of the steels. Zhang [11] revealed that the burst pressure of defect-free X70 pipe without corrosion defect is a function of Y/T. To check this effect, the remaining strain hardening capacity in yield-to-tensile ratio (Y/T) format as function of pre-strain is shown in Fig. 6. As the pre-strain increase, the remaining strain hardening capacity decrease (indicated with increasing of Y/T value near to 1).

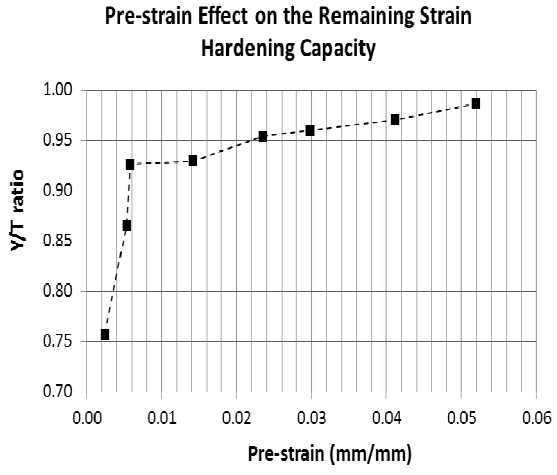


Fig. 6 Pre-strain effect on remaining strain hardening.

3.2 Stress–Strain Response

As known, the yield strength and the tensile strength increased with increasing of tensile pre-strain. It is common in metallic tensile test, the true stress increase by increasing of the true-strain as following power law or constitutive model, including stress-strain curve as reported under pre-strain effect by Baek [4]. Detail model of flow stress behaviour of metals during reloading has proposed by Fernandes [5]. In this present study, the true-stress-strain curve from yield to ultimate point was compared between Fernandes formula (with normalised yield stress $\frac{\sigma_{be}}{\sigma_r}$ during the reloading step by using eq. (4)) and the experimental work. As the result, both curve showed as linear equation. Fernandes formula can be expressed in linear function to the strain as shown in Fig. 8 with slope of the line between 524MPa and 585 MPa (for pre-strain between 2.3% and 5.2%), meanwhile, experimentally the slope is between 1005MPa and 2040 MPa, as shown in Fig. 8.

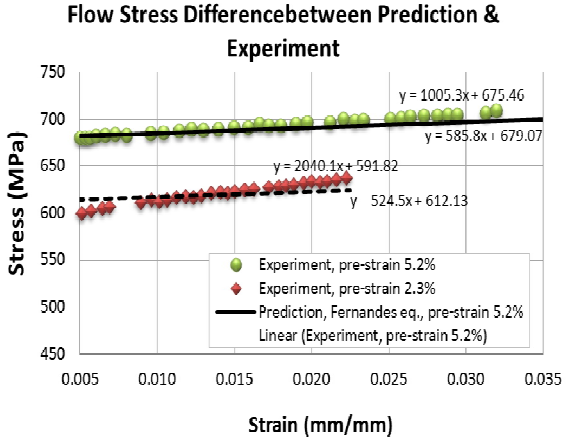


Fig. 8 Slope Difference on the True-Stress-Strain Curve between Experiment and Fernandes Equation.

The line resulted on the tested specimens under pre-strain effect can be expressed as:

$$\sigma^* = a\varepsilon^* + b \qquad (6)$$

where:
a = slope of curve (MPa),
b = yield strength in reloading step (MPa).

CONCLUSION

The paper presents some experimental work for significance in general plasticity aspect of pre-strain effect in pipeline steel body. Pre-strain issue may be not significant (e.g. refer to [12]) for certain cases, however there is limitation of strain capacity needed to be investigated more comprehensive in order to capture another "detrimental effect" of pre-strain which may occur with different type of loading (e.g. repeating load, combined loading in pressurized

pipeline, etc.) and acceptable defect, especially in plastic zone in stress-strain curve. It is concluded in this present study that the true stress-strain curve empirically under pre-strain effect in plastic zone (between yield and ultimate point) can result in linear model.

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