DUCTILE FAILURE ANALYSIS OF API STEEL PIPE USING STRAIN BASED FAILURE CRITERIA

SITI FIRDAUS BINTI MD SALLEH

Report submitted in partial fulfillment of

the requirement for the award of the degree of

Bachelor of Mechanical Engineering

BACHELOR OF MECHANICAL ENGINEERING

UNIVERSITI MALAYSIA PAHANG

JUNE 2013

ABSTRACT

This project was performed to propose ductile failure criteria as a function of the stress triaxiality for the API X42 steel pipes. The objective of this project is to determine the burst pressure of modeled pipe using strain based failure criteria. In this project, uniaxial tension test was performed using three types of specimen. The specimen extracted from API X42 5L steel pipe. The steel pipe was machined to desired dimension and obeys the international standard of ASTM-E8 specimen. Three type of specimen which is smooth, notch radius 1.5 mm, 3 mm and 6 mm prepared and undergoes uniaxial tension test. The engineering stress-stress data retrieved from the test converted to the true stress-strain curve. The true stress-strain data become as an input data to the simulation analysis. Initial and final diameter of specimen was taken to calculate the strain fracture of the pipe. Stress modified critical strain criteria were proposed by using the strain fracture. The findings of the main parameter which is burst pressure predictions precede by using FEA software. Finite Element analysis was performed by using MSC Patran/Marc 2008r1 software. In MSC Patran, the API X 42 steel pipes was modeled. Burst pressure predicted compared to the available industrial pipe design assessment in order to validate the obtained results.

ABSTRAK

Projek ini telah dilaksanakan untuk mencadangkan kriteria kegagalan mulur sebagai tekanan fungsi triaxiality untuk paip keluli API X42. Objektif projek ini adalah untuk menentukan tekanan pecah paip dimodelkan menggunakan kriteria kegagalan berasaskan ketegangan. Dalam projek ini, ujian ketegangan ekapaksi dilakukan dengan menggunakan tiga jenis viiipecimen. Spesimen dikeluarkan dari API 5L X42 paip keluli. Ia telah dimesin untuk menjadi contoh dan menurut standard antarabangsa ASTM-E8. Tiga jenis viiipecimen yang licin, jejari bertakuk 1.5 mm, 3 mm dan 6 mm disediakan dan menjalani ujian ketegangan ekapaksi. Data tegasan-terikan kejuruteraan dari ujian, ditukar kepada graf tegasan-terikan benar. Data telah ditukar dijadikan sebagai input data untuk analisis simulasi. Diameter awal dan akhir viiipecimen telah diambil untuk mengira patah tekanan paip. Terikan kriteria tegasan kritikal yang diubahsuai telah dicadangkan dengan menggunakan tekanan patah. Hasil parameter utama iaitu tekanan ramalan pecah telah diteruskan dengan menggunakan perisian FEA. Analisis Unsur Terhingga dilakukan dengan menggunakan MSC Patran / Marc perisian 2008r1. Dalam MSC Patran, API X 42 paip keluli telah dimodelkan. Bagi mengesahkan keputusan yang diperolehi, tekanan letus yang diramalkan, dibandingkan dengan penilaian reka bentuk paip industry.

TABLE OF CONTENT

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS

σ	stress
σ_y	Yield Strength,
σ_s	Tensile stress
σ_E	Engineering stress
σ_T	True strain
σ_e	Equivalent stress
σ_m	normal (hydrostatic) stress
$\frac{\sigma_m}{\sigma_e}$	Stress triaxiality
ε_e	Engineering strain
ε_T	True strain
ε_f	modeling pipeline fracture strain
ε_f^*	Specimen fracture strain
A_0	Original cross-sectional area
A_f	Final cross-sectional area
L_0	Original length
L_f	Final length
δ	deflection
F	Force
F_0	Original force
F_f	Final force
L	Length of pipe
t	Thickness of pipe
d/t	Ratio of defect depth to the pipe thickness
d	Defect depth
l	Defect length
c	Defect width

LIST OF ABBREVIATIONS

ASTM E8	American Society for Testing and Material E8
API X42	American Pipe Institute X42
ANSI	American National Standard Institute
HAZ	heat affected zone
FEA	Finite Element Analysis
FE	Finite Element
SMCS	Stress Modified Critical Strain
CS	Case Study
ASME	American Society of Mechanical Engineer
UTM	Universal Testing Machine

CHAPTER 1

INTRODUCTION

1.1 RESEARCH BACKGROUND

The long-distance pipeline for transportation of the natural gas, one of the green energy resources, is now under construction in the world wide range, due mainly to the expensive requirement of the energy resources. One of the major difficulties is that, usually, the production area is far from the usage area, resulting in higher transportation cost of the natural gas, although this has been known for many years.

In additions, underground gas pipelines are often subject to damages due to surroundings environment such as corrosion, and the third party accidents such as dents and gouges. The negligence by the human factor will cause those defect. The high costs of maintenance have to be provided to ensure the smooth transportation of the gas.

The installation cost for the thus steel gas pipe higher than the cost of the pipe itself. To minimize those excessive cost, lots of analysis have been proposed and running over a decade. Lots of efforts give to ensure the last longer of the gas transportation's performance.

The study was focusing on API X42 steel pipe material. Three type of sample specimen were machine according to the Tensile testing standard requirement. Tensile test has been performed on the selected material to determine the engineering stress – strain curve. Then, detailed elastic–plastic, finite element analyses perform to simulate tensile tests specimens and thus to determine variations of the triaxial stress and strain.

1.2 PROBLEM STATEMENT

Nowadays, the fitness-for-service analyses of underground gas pipelines, engineering assessment methods against possible effects need to be developed, it will prevent such as corrosion, gouges and dents defects type. Thus possible causes may not distress in a day, but it will bounce on results in few years which consist of extraordinary maintenance cost.

Nothing that, typical gas pipelines are made of sufficiently ductile materials, the net-section limit load approach can be used, where a damaged pipe is assumed to fail at the load when the net section is in the fully plastic state. Meanwhile, design of pipelines is one of the important processes in developing the engineering structure. During design stage, few processes were involved such as analysis of deflections, stress analysis, cost reliability and others.

Stress analysis appears as a crucial process for many engineering structure fail due to lack of consideration on the analysis. One of the important parameters involve in stress analysis is uniaxial fracture strain. The failure on engineering structure normally predicted based on maximum stress that withstand the structure. Unfortunately, the fracture strain becomes critical to be determined.

1.3 PROJECT OBJECTIVES

The research proposes ductile failure criteria as a function of the stress triaxiality for the API X42 steel pipes. Smooth and notched tensile rods with three notch radii are tested to determine parameter of ductile failure criteria. The strain based failure criteria will be applied for failure prediction of the defective API steel pipes. For this purpose, the strain-based criterion will be developing in advance. Otherwise, the burst pressure will be determined for different defect dimension.

1.4 SCOPES OF STUDY

The scopes of research are as follows:

i. Preparation of both smooth and notched specimens
ii. Uniaxial Tension test- at room temperature obey the ASTM E8
iii. Finite Element Analysis
    - MSC PATRAN/MARC
    - Non-linear
    - Homogeneous material
iv. Validations - Compare result between equation and available industrial codes for pipelines defect assessment.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter will provide the detail descriptions literature review done accordingly to tittle of ductile failure analysis of API steel pipe on strain-based failure criteria. Literature regarding any development or experiment about fracture strain and state of stress is useful in this project. This chapter will explain about the fundamentals of API X42 steel pipes, pipelines, engineering stress-strain curve, true stress-strain curve, finite element analysis, and failure criteria that available in this project.

2.2 FUNDAMENTAL OF X 42 API STEEL PIPES

The material used in this study was API X42 steel. Specimens for uniaxial tensile test were extracted in longitudinal direction from pipe. Table 2.1 and 2.2 shows the chemical compositions and mechanical properties of API X42

Table 2.1: Chemical composition of API X42 steel pipe

Sources**:** N.A.Alang (2009)

	C	**P**	**Mn**	**S**	**Fe**
Experimental	0.03	0.01	0.98	0.003	98.6
API SPEC 5L	0.28(max)	0.08(max)	1.3(max)	0.03(max)	Balance

Table 2.2: Mechanical Properties of API X42 steel pipe in room temperature.

	Young Modulus, *E* (GPa)	**Poisson Ratio, *V***	**Yield Strength, σ_y (Mpa)**	**Tensile stress, σ_s (MPa)**
Experimental	207	0.3	284.7	464.4

2.3 PIPELINES

API pipeline tubes belong to ANSI (American National Standard Institute) Petroleum standards. The function of line pipe is to pump the oil, gas, water from field to the refinery. Pipeline tubes include seamless tube and welded tube. The development of pipeline steel plate technology and welding technique widen the application scope of welded pipe. Each of pipe type have their own mechanical properties which as vary it from each other.

Pipelines have been employed as one of the most practical and low price method for large oil and gas transport since 1950. The pipe line installations for oil and gas transmission are drastically increased in last three decades. Consequently, the pipeline failure problems have been increasingly occurred. The economic and environmental and eventually in human life considerations involve the current issue as structural integrity and safety affair.

2.3.1 Defects on Pipes

The explosive characteristics of gas provide high wakefulness about the structural integrity. Therefore, the reliable structural integrity and safety of oil and gas pipelines under various service conditions including presence of defects should be warily evaluated. The external defects, corrosion defects, gouge, foreign object scratches, and pipeline erection activities are major failure reasons of gas pipelines.

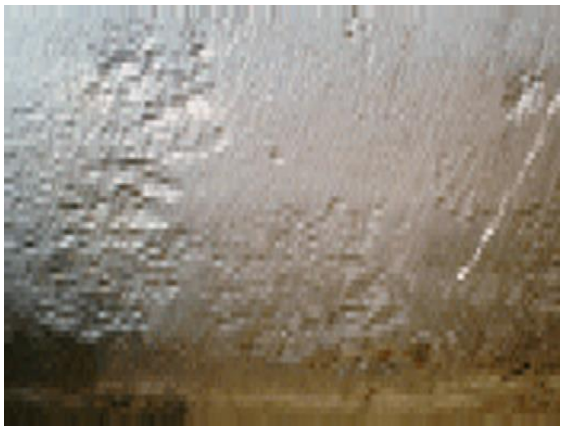

Figure 2.1: External corrosion defect on pipe

Source**:** M.Hadj, 2010

A typical external of a corrosion defect is given in Figure 3.1. Several types of pipes failures can be distinguished as longitudinal, circumferential or helicoidally failures (M.Hajd,Y.G Matvienko, G. Pluvinage, 2010) . These types depend mainly on pipe diameter. For small diameter pipes, where bending stresses are the major, circumferential failure occurs. For large diameters, hoop stresses are more important than bending stresses and longitudinal failure appears. When bending and hoop stresses are of the same importance, fracture path becomes spiraled. Pipe steels have yield stress up to 700 MPa for the most recent quality in order to ensure enough ductility and weld ability.

Defects occurring during the fabrication of a pipeline are usually assessed against recognized and proven quality control limits. However, a pipeline will regularly contain

larger defects at some stage during its life and these will require a fitness- for-purpose assessment to determine whether or not to repair the pipeline.

Line pipe steels is generally tough and ductile. Initiation and propagation of a part-wall flaw through the wall occurs under a ductile fracture mechanism, involving some combination of plastic flow and crack initiation and ductile tearing, involving a process of void nucleation, growth and coalescence. The relative importance of plastic flow and crack initiation and tearing depends on the toughness of the material and the geometry of the defect.

As the toughness decreases the burst strength of a defect will decrease. As the toughness increases the burst strength of a defect will increase, but tending towards an upper limit corresponding to the plastic collapse limit state, where failure occurs due to plastic flow .Therefore, if the toughness is greater than some minimum value then the failure of a defect will be controlled by plastic collapse and only knowledge of the tensile properties of the material is required to predict the burst strength.

Corrosion is an electrochemical process. It is a time dependent mechanism and depends on the local environment within or adjacent to the pipeline. Corrosion usual appears as either general corrosion or localized (pitting) corrosion. There are many different types of corrosion, including galvanic corrosion, microbiologically induced corrosion, AC corrosion, differential soils, differential aeration and cracking. Corrosion causes metal loss.

It can occur on the internal or external surfaces of the pipe, in the base material, the seam weld, the girth weld, and or the associated heat affected zone (HAZ). Internal and external corrosion are together one of the major causes of pipeline failures. Figure 2.2 shows example of worse corrosion effect on the pipeline. It will cause higher maintenance cost and wasting time.

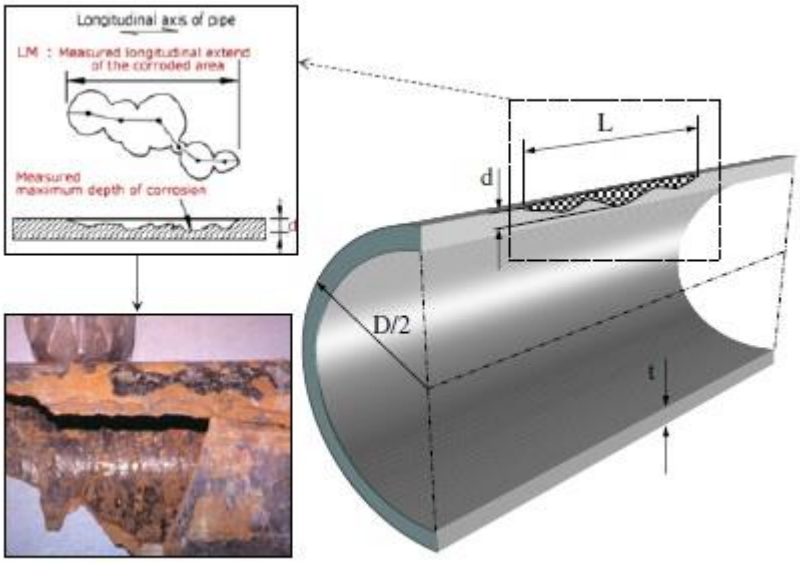

Figure 2.2: Corrosion on the pipeline

Sources**:** M.Hajd, 2010

Corrosion in a pipeline may be difficult to characterize. Typically, it will have an irregular depth profile and extend in irregular pattern in both longitudinal and circumferential directions it may occur as a single defect or as a cluster of adjacent defects separated by full thickness (uncorroded) material.

There are no clear definitions of different types of corrosion defects. The simplest and perhaps most widely recognized definitions are as pitting corrosion. It defined as corrosion with a length and width less than or equal to three times the uncorroded wall thickness. While, general corrosion, defined as corrosion with a length and width greater than three times the uncorroded wall thickness.

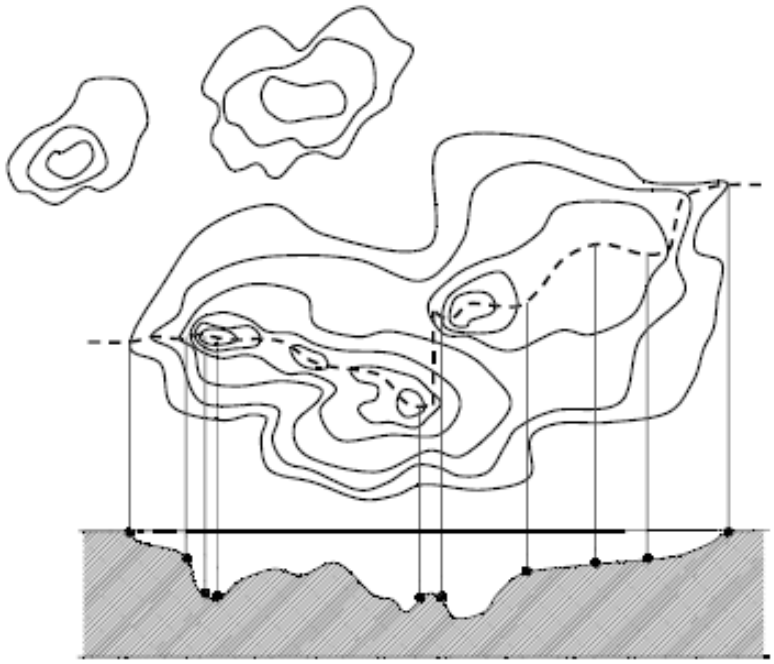

Figure 2.3: The irregular length, width and depth of a typical corrosion defect.

Source**:** A.Cosham, 2007

2.4 ENGINEERING STRESS-STRAIN CURVE

Stress-strain curves are an extremely important graphical measure of an API steel pipe material's mechanical properties. Perhaps the most important test of a material's mechanical response is the tensile test. The engineering measures of stress and strain, denoted in this module as σ_e and ε_e respectively, are determined from the measured the load and deflection using the original specimen cross-sectional area A_0 and length L_0 as

$$\sigma_e = \frac{P}{A_0} \tag{2.1}$$

$$\varepsilon_e = \frac{\delta}{L_0} \tag{2.2}$$

When the stress σ_e is plotted against the strain ε_e, a typical engineering stress-strain curve such as that shown in figure 2.4 is obtained.

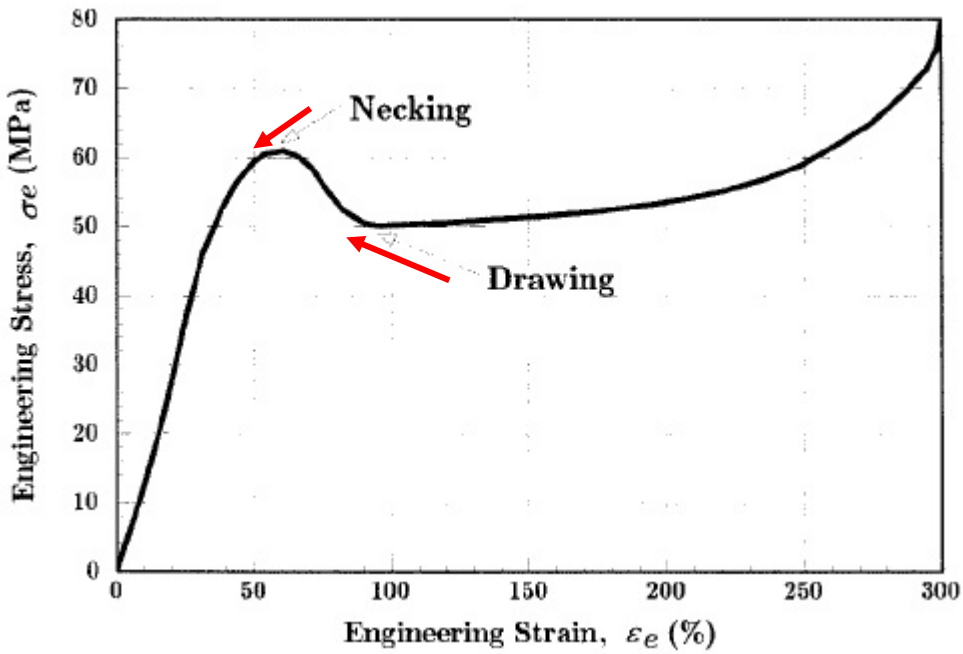

Figure 2.4: Stress-strain curve

Sources**:** David, 2001

As strain is increased, many materials eventually deviate from this linear proportionality, the point of departure being termed the proportional limit. This nonlinearity is usually associated with stress-induced "plastic" flow in the specimen. Here the material is undergoing a rearrangement of its internal molecular or microscopic structure, in which atoms are being moved to new equilibrium positions. This plasticity requires a mechanism for molecular mobility, which in crystalline materials can arise from dislocation motion. Materials lacking this mobility, for instance by having internal microstructures that block

dislocation motion, are usually brittle rather than ductile. The stress-strain curves for brittle materials are typically linear over their full range of strain, eventually terminating in fracture without appreciable plastic flow. The stress needed to increase the strain beyond the proportional limit in a ductile material continues to rise beyond the proportional limit; the material requires an ever-increasing stress to continue straining, a mechanism termed strain hardening.

These microstructural rearrangements associated with plastic flow are usually not reversed when the load is removed, so the proportional limit is often the same as or at least close to the material's elastic limit. Elasticity is the property of complete and immediate recovery from an imposed displacement on release of the load, and the elastic limit is the value of stress at which the material experiences a permanent residual strain that is not lost on unloading. The residual strain induced by a given stress can be determined by drawing an unloading line from the highest point reached on the curve at that stress back to the strain axis.

Until the neck forms, the deformation is essentially uniform throughout the specimen, but after necking all subsequent deformation takes place in the neck. The neck becomes smaller and smaller, local true stress increasing all the time, until the specimen fails. This will be the failure mode for most ductile metals. As the neck shrinks, the nonuniform geometry there alters the uniaxial stress state to a complex one involving shear components as well as normal stresses.

2.5 TRUE STRESS STRAIN CURVE

While stress testing, the stress-strain curve is a graphical representation of the relationship between stress, obtained from measuring the load applied on the sample. Meanwhile, strain derived from measuring the deformation of the sample. The nature of the curve varies depends on the type of materials. Strain describes quantitatively the degree of deformation of a body. It is measured most commonly with extensometers and strain gauges. For uniaxial deformation strain can be expressed as

$$\varepsilon_e = \frac{L_f - L_0}{L_0} \tag{2.3}$$

Where

ε_e = engineering strain

L_0 = original length of the undeformed specimen

L_f = final length of the deformed specimen

Based on this definition, if a sample were stretched such that $L_f = 2L_0$, the tensile engineering strain would be 100%. On the other hand, if a sample were compressed to the limit such that $L_f = 0$, the compressive engineering strain would again be 100%. These extreme examples show that for large strain the definition of equation (2.3) is not meaningful.

For purely elastic deformation stresses are uniquely defined by the final configuration of a material, regardless of how this final state is reached. Because of the presence of irreversible elements in the deformation a plastic analysis has to follow the path along which the final configuration is reached. So that, the total deformation is generally divide into small increments.

Considering the uniaxial case, let dL be the incremental change in gauge length and L the gauge length at the beginning of that increment. Then, the corresponding strain increment becomes

$$d\varepsilon = \frac{dL}{L} \tag{2.4}$$

and the total strain for a change of the gauge length from L_0 to L_f

$$\varepsilon = \int_0^{\varepsilon} d\varepsilon = \int_{L_0}^{L_f} \frac{dL}{L} = ln\,\frac{L_f}{L_0} \tag{2.5}$$