To my dear beautiful mother, my dear decent father, my beloved wife,
and my lovely daughter.

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ABSTRACT

In optimal design of thick-walled cylinder, there are two main objectives to be achieved, increasing its strength-to-weight ratio and extending its fatigue life. This can be achieved by generating a residual stress field in the cylinder wall prior to use, a process known as autofrettage. Two different cylindrical components are proposed in this study; a plain and a stepped thick-walled cylinders. They are modelled using two-dimensional axisymmetric elements, and analysed for optimisation of autofrettage pressure and fatigue life. A Finite Element (FE) Method using ABAQUS is carried out on the cylinders to develop a procedure in which the autofrettage process is determined numerically, resulting in a reduced maximum equivalent stress distribution. Cylindrical pressure vessels often have a fluctuating internal pressure load and can fail through fatigue. For this purpose a fatigue life evaluation of the cylinders is performed, using FE-SAFE, to evaluate the structural integrity of autofrettaged vessels. A technique for elastic-plastic analysis of thick-walled cylinder under internal operating pressure is proposed where the performance of the cylinders is evaluated for different levels of autofrettage. The results reveal three scenarios in the design of thick-walled cylinders. For maximum load carrying capacity, non-autofrettage is suitable when, in service, the whole wall thickness will be yielded. Full autofrettage is suitable when, during subsequent operation, yielding is limited at the inner surface. Optimum autofrettage of the cylinder is suitable if a minimum equivalent stress is to be achieved. FE simulation shows that the effect of external step on the optimum autofrettage is not significant. Experiments are carried out to validate the numerical results of residual stress. There is a good agreement between the FE simulation and the strain measurements. In fatigue analysis, the fatigue life initially increases with autofrettage level, reaching a maximum optimum level and then decreases. The optimum autofrettage leads to an optimum fatigue life which is found to be about 3.24 times greater than non-autofrettaged cylinders. The analytical solutions are compared to numerical results and a very good correlation in form and magnitude is obtained.

ABSTRAK

Dalam rekabentuk optimum silinder berdinding tebal, terdapat dua objektif utama yang perlu dicapai, iaitu menambah nisbah kekuatan terhadap berat dan melanjutkan jangka hayat lesunya. Ini dapat dicapai dengan mewujudkan medan tegasan baki dalam dinding silinder melalui proses 'autofrettage'. Dua struktur silinder berbeza telah dicadangkan dalam kajian ini iaitu silinder biasa dan silinder bertangga. Struktur ini telah dimodelkan menggunakan elemen paksi simetrik dua dimensi dan telah dianalisiskan untuk tahap optimum tekanan 'autofrettage' dan jangka hayat lesunya. Perisian Kaedah Unsur Terhingga ABAQUS telah diaplikasikan ke atas silinder bagi membentuk prosedur di mana proses 'autofrettage' dibangunkan dari kaedah berangka, yang akan menghasilkan pengurangan agihan tegasan maksimum. Tabung tekanan berbentuk silinder selalunya mempunyai tekanan dalaman yang berkitar, dan boleh mengalami kegagalan lesu. Bagi tujuan ini, penilaian terhadap jangka hayat lesu silinder ditentukan dengan menggunakan FE-SAFE bagi menentukan keselamatan silinder yang telah di'autofrettage'. Analisis elastik-plastik di bawah tekanan kerja telah dicadangkan, dimana prestasi silinder akan dinilai pada tahap 'autofrettage' yang berlainan. Hasil kajian menunjukkan tiga senario dalam rekabentuk silinder berdinding tebal. Untuk menampung tekanan yang paling tinggi, ketiadaan 'autofrettage' adalah sesuai, di mana keseluruhan ketebalan dinding silinder mengalami alahan. 'Autofrettage' penuh sesuai apabila dalam penggunaan, alahan berlaku pada permukaan dalaman. Seterusnya, 'autofrettage' optimum sesuai digunakan apabila tegasan minimum diperlukan. Kaedah eksperimen telah dijalankan bagi mengesahkan hasil kaedah berangka tegasan baki. Terdapat hubungan baik di antara simulasi FE dan pengukuran terikan. Dalam analisis lesu, pada permulaan, jangka hayat lesu meningkat dengan peningkatan tahap 'autofrettage', kemudian mencapai tahap optimum dan kemudiannya akan merosot. Tahap optimum 'autofrettage' membawa kepada jangka hayat lesu yang optimum dan kesan tangga keatas 'autofrettage' optimum adalah tidak signifikan. Penyelesaian analitikal dibandingkan dengan hasil kaedah berangka dan ianya mempunyai korelasi yang baik dari segi bentuk dan magnitud.

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LIST OF ABBREVIATIONS

ABBREVIATION		DISCRIPTION
2D	-	Two-Dimensional
3D	-	Three-Dimensional
FEM	-	Finite Element Method
FEA	-	Finite Element Analysis
FDM	-	Finite Different Method
FVM	-	Finite Volume Method
HCF	-	High Cyclic Fatigue
LCF	-	Low Cyclic Fatigue
LCT	-	Lower Critical Temperature
XRD	-	X-Ray Diffraction techniques
CNC	-	Computer Numerical Control
ASTM	-	American Society for Testing and Materials

LIST OF SYMBOLS

SYMBOL		DISCRIPTION
P	-	Pressure
r	-	Radius
t	-	Thickness
k	-	Outer/Inner Radius Ratio
m	-	Autofrettaged/Inner Radius Ratio
n	-	Operating Pressure/Yield Stress ratio
σ	-	Stress
τ	-	Shear Stress
R	-	Residual
T	-	Total
c	-	Fatigue Ductility Exponent
ε'_f	-	Fatigue Ductility Coefficient
σ_m	-	Mean Stress in Cycle
$\Delta\varepsilon$	-	Applied Strain Range in Cycle
N_f	-	Cycles to Failure
σ'_f	-	Fatigue Strength Coefficient
$\Delta\sigma$	-	Applied Stress Range in Cycle
b	-	Fatigue Strength Exponent
H, h	-	Step height of cylinder.

LIST OF SUBSCRIPTS

SUBSCRIPTS		DISCRIPTION
i	-	inner
o	-	outer
a	-	autofrettage
r	-	radial
θ	-	hoop
z	-	axial
y	-	yield
p	-	plastic
e	-	elastic
1,2,3	-	principal directions
opt	-	optimum
opr	-	operating
max	-	maximum
min	-	minimum
Tr	-	Tresca
vM	-	von-Mises

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CHAPTER 1

INTRODUCTION

1.1 Background of The Problem

As the economic and environmental push for conservation of raw materials and weight reduction of components continue, engineering design will continue to move towards strong and safer components with more efficient use of material strength. Due to the ever-increasing industrial demand for axisymmetric pressure vessels which have had wide applications in chemical, nuclear, fluid transmitting plants, power plant, pipeline, and military equipment, the attention of designers has been concentrated on this particular branch of engineering. The increasingly scarce material and higher cost have led researchers not to confine themselves to the customary elastic regime but attracted their attention to the elastic-plastic approach which offers more efficient use of material.

Analytical solutions of thick-walled cylinders become complicated because of the non-linear stress-strain relation. When a thick-walled cylinder is internally pressurised the internal surface is the most highly stressed part of the cylinder. With further increase in pressure, the inner surface begins to yield and the yield surface begins to propagate along the thickness of the vessel, until it reaches the outer surface. When the cylinder material is entering the plastic regime, the material begins to strain harden. When the weakening caused by yielding exceeds the strengthening caused by strain hardening, the cylinder will fail at the maximum ultimate pressure [1].

Autofrettage is a plastic deformation process caused by imposing a very high internal pressure, resulting in compressive and tensile hoop residual stresses at the inside and outside surfaces of the cylinder, respectively. These result in increased load carrying capacity, gross resistance to fatigue and inhibit the rate of crack propagation [2]. The autofrettage process introduces favourable residual compressive stresses in the region of expected high tensile stresses. This process has allowed a higher service pressure in the vessel and has decreased cylinder susceptibility to inner surface cracking.

Residual stresses are defined as stresses that exist within a body in the absence of external loading. Such stresses are the result of a field of inhomogeneous strains within the body. The elastic constraints of material surrounding the inhomogeneous strain leads to the residual stress field within the body and geometric changes in the body are necessitated by the requirements of force equilibrium. There are numerous methods of introducing residual stress into mechanical component; they include shot peening; interference fit fastening, low plasticity burnishing, laser shock peening, tensile overloading, cold expansion, and autofrettage. It is well known that autofrettage process creates residual stresses in the wall of thick cylinders. Depending upon their nature, these residual stresses can have significant effects upon cylinder life by influencing fatigue, creep, and stress corrosion cracking resistance. On the other hand, autofrettage induced residual stresses can have detrimental effects upon thick-walled cylinders because autofrettage process reduce the maximum internal pressure to cause the whole wall thickness of cylinder to yield. Thus, it is of significant industrial importance to predict the nature of autofrettage induced residual stresses in a cylinder, based upon the autofrettage pressurised conditions and material behaviours [3]

Fatigue is the source of at least half of all mechanical failures [4]. Fatigue problem is complex and not fully understood, but it is very important in the design of mechanical systems. Fatigue is especially of interest to the pressurised equipment industry. For cylinders that are designed to operate at the envelope of strength, those that experience cyclic loading, in an aggressive atmosphere or any combination of these, autofrettage induced residual stresses can have profound effects by limiting fatigue failure. Fatigue cracks generally form and propagate at the inner surface of a thick-walled cylinder subjected to cyclic internal operating pressure, where the maximum tensile hoop stress occurs.

The cylindrical vessel part usually has a fluctuating internal operating pressure load and may fail by fatigue loads. Many studies have investigated plain thick-walled cylinders based on the minimization of maximum stress to improve the cylinder lifetime. In this study, an autofrettage process technique is developed to obtain optimum stress redistribution under fatigue loads.

1.2 Pressure Vessel Technology

The origin of high pressure technology can be traced back to the fourteenth century when the first known cannons were invented. Today, high pressure technology has developed from early basic science to major applications that have driven the technology. The advances of high pressure technology were based on the theoretical understanding of thick-walled cylinder subjected to internal pressure. Thick-walled cylinders subjected to high internal operating pressure are widely used in various industries. In general, vessels under high internal require a strict analysis for an optimum design for reliable and secure operational performance. Efforts have been continually made to obtain a thorough understanding of the behaviour of the pressurized thick-walled cylinder and to increase reliability of design.

Pressure vessels and thick-walled cylinders are one of the most important and expensive engineering components. Their usage ranges from simple design air bottles and liquid petroleum gas (LPG) to highly sophisticated designs of artillery gun barrels, ballistic missiles and nuclear reactors. Safety consideration is an important issue and during designing and manufacturing of these parts, quality must be assured. To accomplish this, proof pressure, non-destructive inspection, destructive testing, modelling and simulation techniques are extensively used [5].

Failure analysis and failure prevention are important functions in all engineering disciplines. The materials engineer often plays a lead role in the analysis of failures, whether a component or product fails in service or if failure occurs in manufacturing or during production processing. One must determine the cause of failure to prevent future occurrence, and to improve the performance of the component or structure. Nowadays, designers are demanding for high quality with low cost, more importantly, a product with high reliability and safety to reduce the warranty cost. Therefore, improving the limits of safety and reliability of pressurized components is an important challenge for pressure vessel designer. The human cost of failed structures has been documented throughout history by accidents ranging from airline disasters to catastrophic bridge and building collapse.

Design optimization using only a sizing design variable is fairly straightforward to implement: the shape of the structure remains unchanged so that no refinement or modification is required for the finite element geometry model. As a consequence, it is easy in this case, to implement design sensitivity analysis. However, there exists an important class of structural design problems in which the shape of the structure has to be determined. Most engineering components contain discontinuities in their geometric features. These cross-sectional changes appear in many forms such as fillets, threads, holes and steps. These notches are locations where high localized stresses and associated strains are induced and therefore their effects, in the form of stress or strain concentrations, must be considered in the design assessment of these components, especially when subjected to variable or cyclic loading.

A few published studies have examined the boundary shape of two-dimensional plane problems and very little work has been published about shape effect of axisymmetric thick-walled cylinder under the action of internal pressure [6, 7, and 8]. The aim of the present study is to determine the increase in the load-carrying capacity and fatigue life which could potentially be achieved in nonstandard pressure cylinder geometries. The results described here contribute to a better understanding of the role geometric discontinues play in reducing the strength of autofrettaged pressurized stepped thick-wall cylinders. Further, this research opens up investigation on the optimization of autofrettage pressure in cylindrical-shaped vessels based on load-carrying capacity. In this study, a procedure for optimizing the performance of plain autofrettaged axisymmetric pressurized thick-walled cylinders with respect to stress re-distribution in critical stepped area is described using the numerical computer simulation analysis packages ABAQUS, and FE-SAFE.

In the design and analysis of components, it has become increasingly important to develop methods that are less sophisticated, more understandable, and easy to apply, but adequately accurate. Design of components such as high pressure thick-walled cylinder in mechanical and general industries requires elastic-plastic analysis. One reason for this is the need to accurately predict residual stresses. Compressive residual stresses in many applications such as autofrettage of cylinders, apart from increasing the pressure capacity of the component, enhance the component fatigue life. The presence of these beneficial residual stresses reduces the probability of crack initiation and slows the growth of fatigue cracks.

The theory of plasticity is not fully exploited by practicing engineers because of the difficulties in applying these mathematically sophisticated techniques. Usually it takes considerable effort to understand and implement techniques for plastic analysis. In most cases, industries are not convinced of the resulting economy and hence consider such analysis unaffordable. Alternative methods of elastic-plastic analysis have attracted special attention recently. These methods provide simpler techniques to approximate the elastic-plastic behaviour of components and therefore are more attractive to practicing engineers.

1.3 Problem Identification and Objectives

Industrial pressure vessels are usually structures with complex geometry containing numerous geometrical discontinuities and are often required to perform under complex loading conditions such as internal pressure, external force, and thermal load. Cylinders subjected to high internal pressure are widely used as elements of many important constructions. Optimization has become a significant area of development, both in research and practice, in mechanical and structural design. The growing importance of residual stresses in thick-walled cylinders demands an understanding of the autofrettage process and the development of serviceable model for the prediction of autofrettage-induced residual stresses from conventional processes such as pressurizing.

The main objective of the current research is to find the optimum condition of “re-distribution of stresses” of plain and external stepped pressurized thick-walled cylinders which are subjected to an operating internal pressure. The procedure includes analyzing the effect of the residual stresses, which is created by autofrettage process, on radial and tangential hoop stresses, leading to optimum performance, and to the optimum fatigue life. The major steps of this research, for both plain and stepped thick wall cylinders are delineated below:

- To formulate the autofrettage procedures.
- To prove analytically and by simulation that the optimum autofrettage pressure leads to optimum total stress re-distribution in thick-walled cylinder, when an internal operating pressure as specified.
- To find the effect of optimum autofrettage on the performance of thick-walled cylinder.

- To determine the effect of the step height of stepped thick-walled cylinder on optimum autofrettage pressure and radius.
- To validate the effect of residual stresses caused by optimum autofrettage process on pressurizing limits and fatigue life prediction of thick-walled cylinders.
- To establish the fatigue life prediction of thick-walled cylinders which are not treated and treated with optimum autofrettage pressure.

In this research, an effort has been made to determine an analytical and numerical finite element solution that most closely represents the actual thick-walled cylinder autofrettage process. The flow chart in Figure 1.1 describes the major scope of the current research.

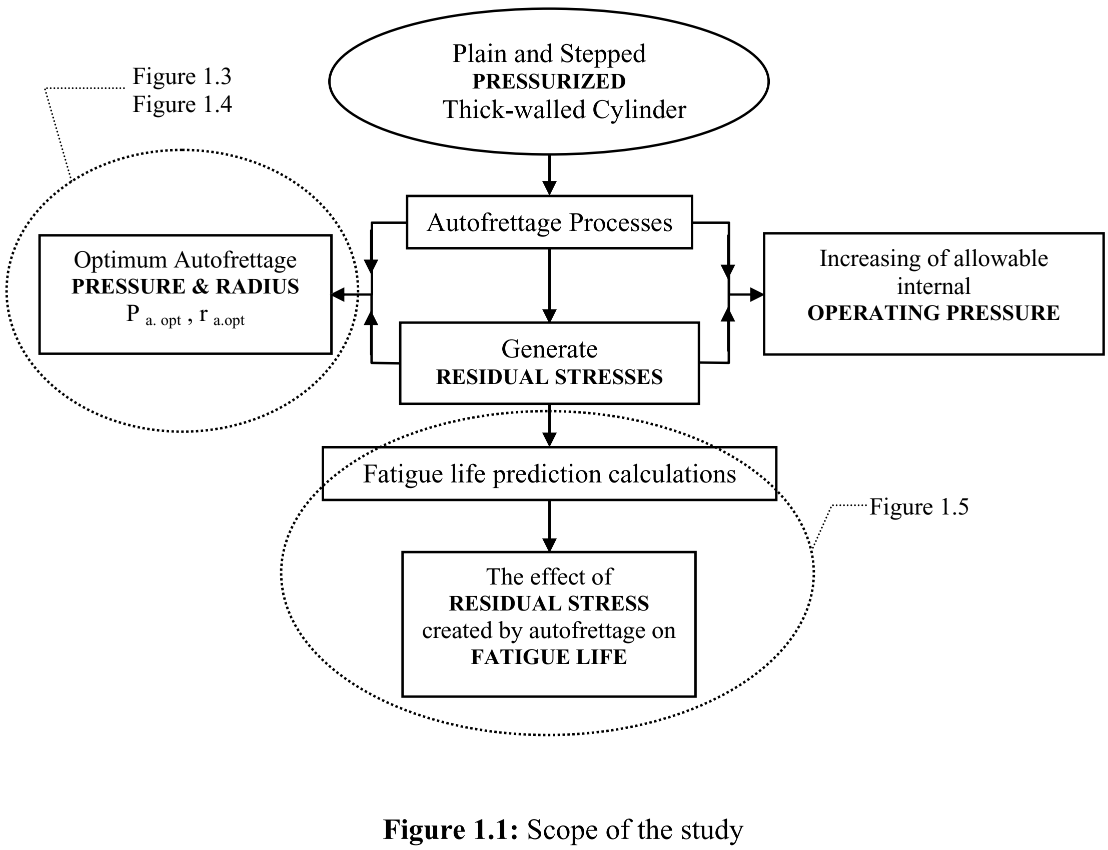

Figure 1.1: Scope of the study

1.4 Methodology

The goals are mainly achieved by analytical procedures which are then verified by experimental investigation and finite element method. This research covers the study of stress distribution and re-distribution of plain and externally stepped thick-walled cylinders, subjected to cyclic internal operating pressure after being autofrettaged. These geometry and sample used for the components are shown in Figure 1.2. The numerical method of analysis is carried out by using the finite element method ABAQUS package, and for fatigue life prediction, the FE-SAFE package is used. The research methodology flowcharts systematically highlighting the major work of the study, are shown in Figures 1.3, 1.4, and 1.5

Figure 1.3 describes the process for obtaining the optimum autofrettage pressure and radius, for plain thick-walled cylinder which was subjected to a known operating pressure. Because the analytical solutions for stepped thick-walled cylinder are not available, only the numerical approach was used. The focus of this study was to investigate the effect of various step heights on the optimum autofrettage pressure and radius, as shown in Figure 1.4.

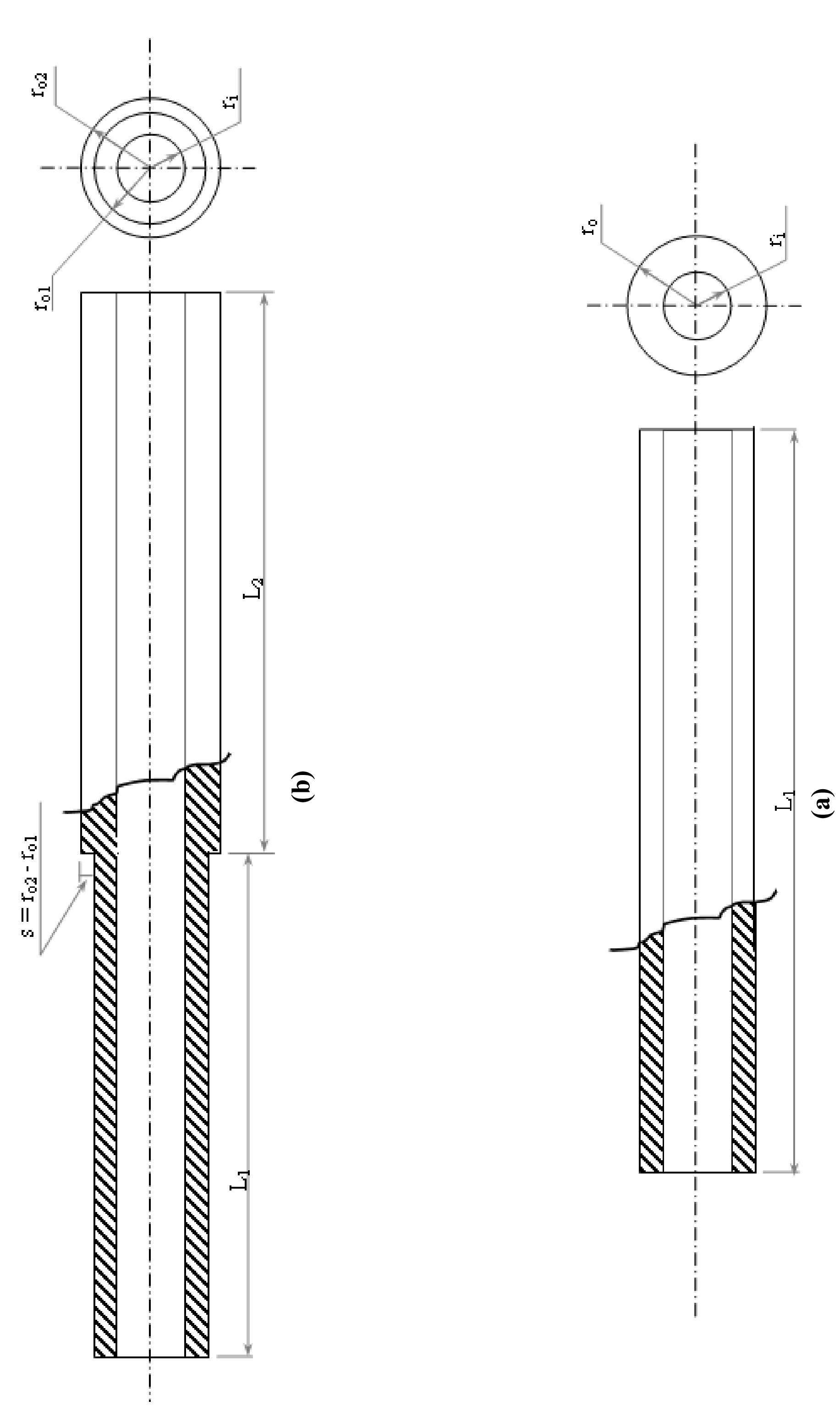

Figure 1.2: (a) Plain and **(b)** stepped pressurized thick-walled cylinders

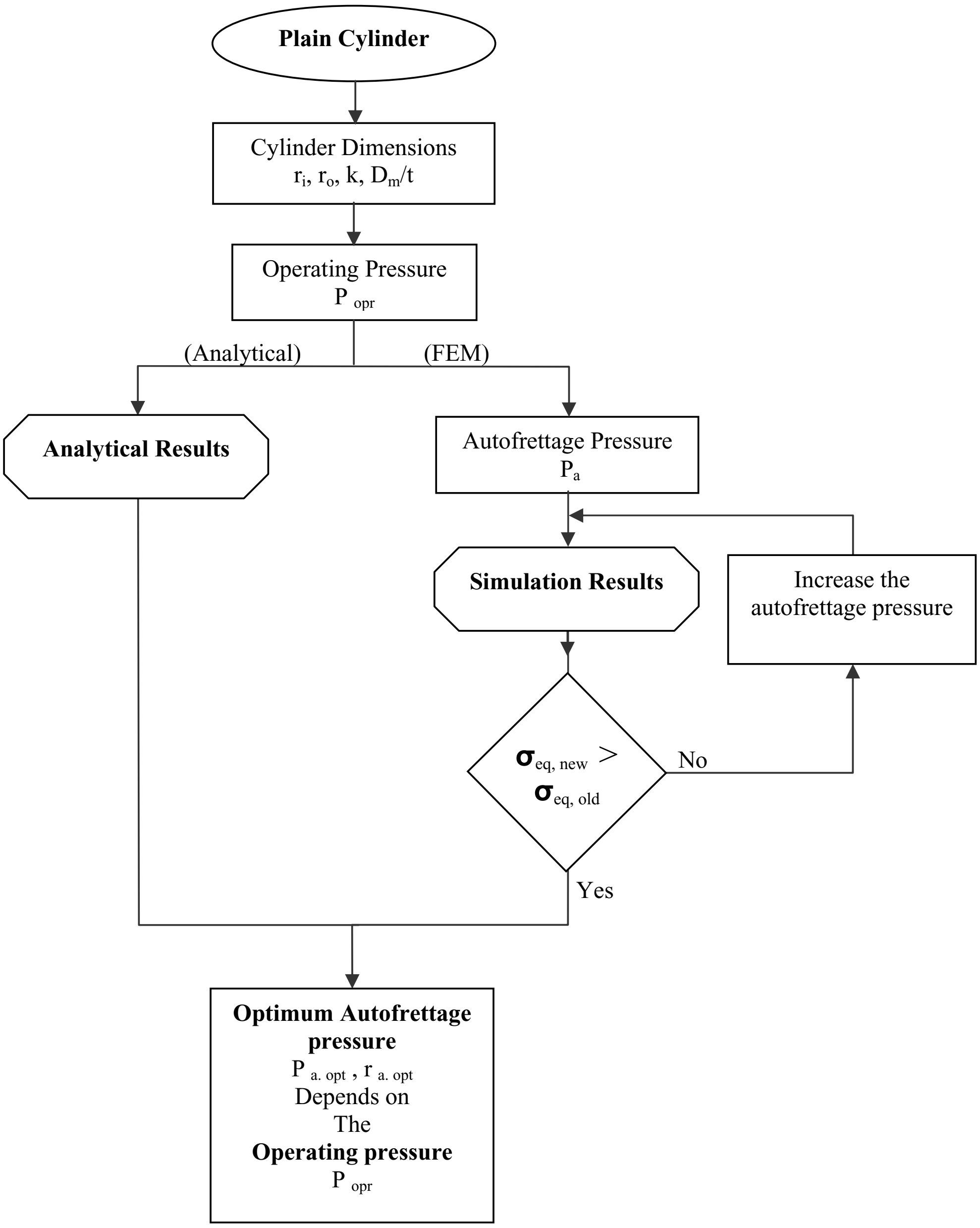

Figure 1.3: Optimum autofrettage procedure of plain thick-walled cylinder

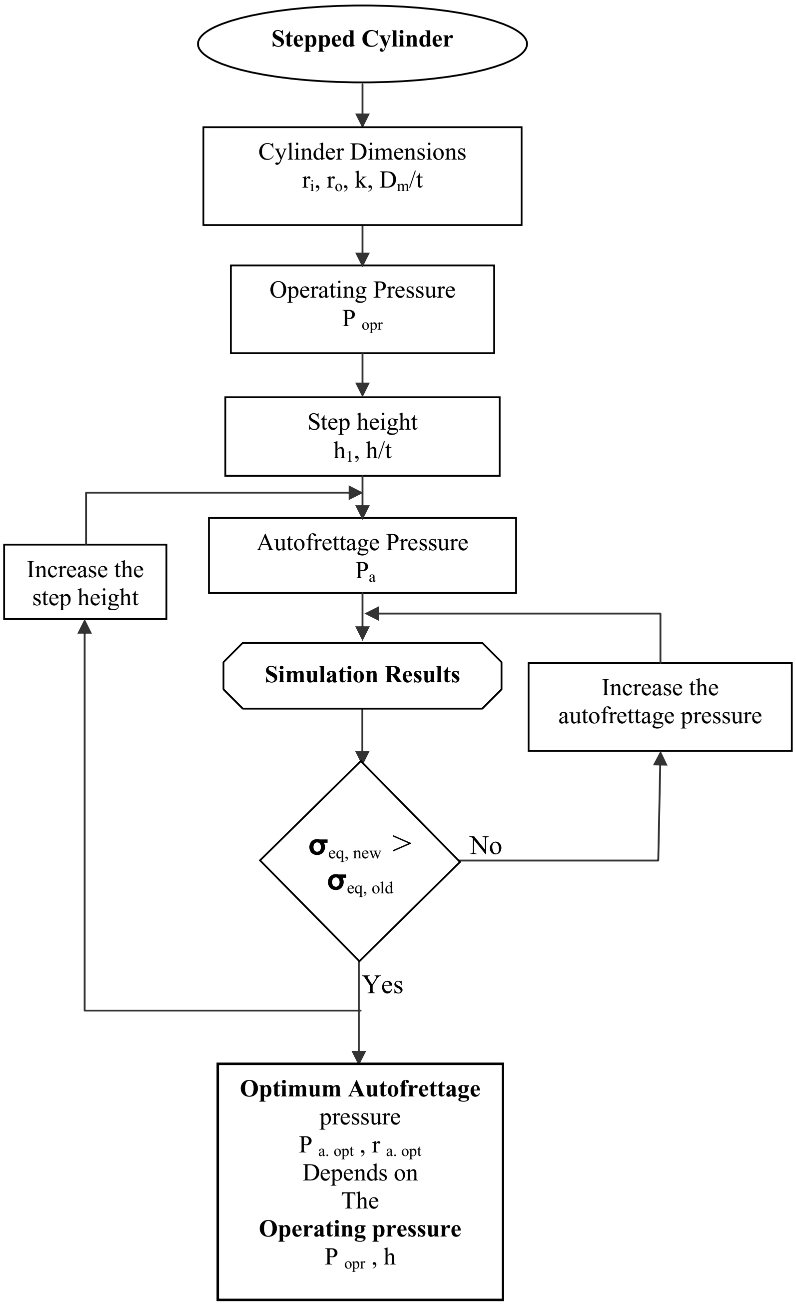

Figure 1.4: Optimum autofrettage procedures of stepped thick-walled cylinders.

To increase the maximum allowable operating pressure in the cylindrical vessel as well as to reduce the vessel susceptibility to cracking, desired residual stresses are introduced in the cylinder wall, usually by the autofrettage process. Figure 1.5 illustrates the numerical procedures of fatigue life prediction of plain and stepped thick-walled cylinder which was subjected to cyclic internal operating pressure after being treated with optimum autofrettage pressure and comparison the results with the life of non-autofrettaged cylinders.

An experimental work was carried out on the cylinder specimens, firstly, with an annealing treatment to recover the material properties and remove the residual stresses which was generated through the machining and welding process, followed by a tensile test to determine the actual material properties. Secondly, the pressure testing of the cylinders was carried out to measure the residual stress at the outer surface. This was then followed by microhardness test to find the elastic-plastic boundary line using the effect of plastic deformation on material Hardness. The analytical and numerical approaches are used to verify the experimental data. Figure 1.6 shows the aim of the experimental procedure of this research.

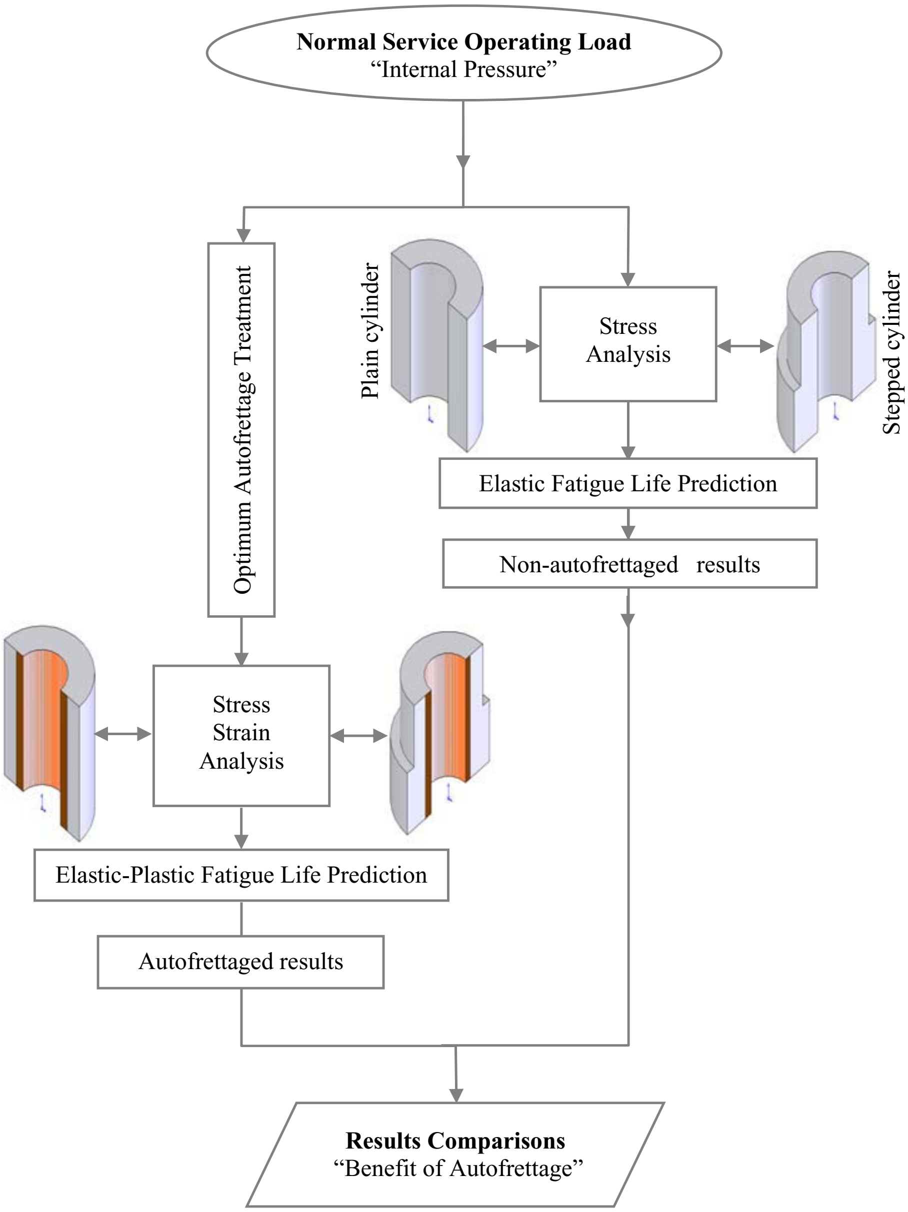

Figure 1.5: Fatigue analysis procedure

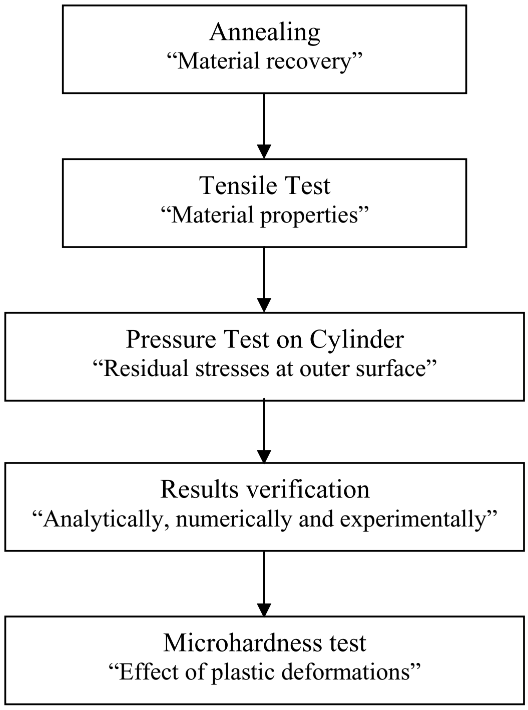

Figure 1.6: Experimental procedure

1.5 Thesis Organization

The thesis consists of eight chapters. The current chapter discusses the problem definition, justification for carrying out the research, and objectives. The chapter is introduced with the industrial application of the topic of high pressure technology, followed by various elastic-plastic analyses for pressurized thick-walled cylinders.

Chapter 2 reviews some of the previous researches on residual stresses created by autofrettage procedures and fatigue life of thick-walled cylinders. The research also discusses residual stresses and fatigue life prediction based on elastic-plastic concept.

A brief description and discussion of the basic fundamentals of stress-strain relationship are introduced in Chapter 3. These should be viewed as background material for the research reported in Chapter 4. Besides that, the fundamental concepts and theories that are related to the research are reviewed in this chapter.

Chapter 4 details a generalized method for analysis of thick-walled cylinders subjected to high internal operating pressure with autofrettage procedures to create residual stresses. Here the analytical formulations for optimum autofrettage pressure and optimum autofrettage junction line (radius) are derived.

Numerical investigations using finite element models are given in Chapter 5. The problems are solved through different commercial Finite Element codes, ANSYS, ABAQUS, and the FE-SAFE.

In Chapter 6, the experimental procedures began with tensile specimen preparation and testing to determine the material properties. It was followed by thick-walled pipe fabrication for pressure testing and residual strain measurements in the pipes which were autofrettaged. The chapter then discusses preparation of the microstructures samples and observation.

Chapter 7 discusses the analytical results and compared with numerical analysis. The experimental data are discussed and compared with the analytical and numerical results.

The conclusions are stated in Chapter 8 together with the summary of the findings of the research and suggestions for other areas of additional research.