Design Procedures for High Temperature Components using Finite Element Methods

by

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Declaration

This is to certify that the results, calculations and any other work presented in this thesis are essentially my own work, and that no part of it has been submitted for a degree at any other university.

Cameron Hulett
May 1993
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Abstract

A procedure for design and redesign of high temperature components is developed. The thesis begins with a description of an engineering problem, namely the failure of a steel plant pre-reduction kiln, which incorporates a number of commonly occurring design problems. A redesign procedure, which follows a more prescriptive rather than a descriptive method, is established for the case study. An investigation of the material properties, loading conditions and component failure is undertaken. Each investigation begins with an overall view of the topic, which is then narrowed to suit the case study. The procedure developed during the investigations begins by using conventional theoretical techniques to determine the material properties and loadings involved. Simple and then more detailed finite element modelling establishes more accurate results for some complicated problems. In particular the thermal loading of the kiln is found to be considerably larger than the self weight loading. Failure analysis techniques together with a sophisticated non-destructive testing technique, Holographic Interferometry, are employed to investigate flaws and failure modes. The technique developed enables the qualification and quantification of material properties and flaws for in situ components. The dominant failure mode for the kiln is stress corrosion which can be prevented by avoiding corrosion and lowering the thermal stresses. However the existence of flaws enables fatigue failure to occur. The procedure continues with a life assessment due to fatigue, however in the kiln case study, the validity of this is uncertain due to insufficient test data. Recommendations for redesign are then given. The design procedure enables an ordered and effective means of solving in situ component failure and redesign problems.
# Table of Contents

Declaration ii  
Acknowledgements iii  
Abstract iv  
Table of Contents v  

1. Introduction 1  
   1.1 Problem Statement 1  
   1.2 Objectives 3  

2. Data Collected on Problem 4  
   2.1 History of Rotary Kilns at Highveld 4  
   2.2 The Kiln Operation and Process 4  
   2.3 The Basic Kiln Design 6  
   2.4 Major Kiln Problems 7  
      2.4.1 Refractory Decay 7  
      2.4.2 Shell Cracking 8  
   2.5 Completed Tests on Kilns 9  
      2.5.1 Process and Performance Tests 9  
      2.5.2 Temperature Profile Tests 10  
      2.5.3 Refractory Investigation 10  
   2.6 Past Kiln Related Ventures 11  
      2.6.1 Changing Refractory Thickness 11  
      2.6.2 Blasting Out Refractory 11  
      2.6.3 Spraying Water on Kiln Shell 12  
      2.6.4 Welding up of Cracked Kilns 12  
      2.6.5 Adding Gussets to Kiln Riding Rings 13  

3. Literature Survey 15  
   3.1 Design Procedures 15  
      3.1.1 Design Process 16  
      3.1.2 Design Methods 20  
   3.2 Material Properties 23  
      3.2.1 Properties of Carbon Steel 23  
      3.2.2 Properties of Refractory Concrete 25  
   3.3 Failure Modes Related to the Steel Shell 28  
      3.3.1 Creep 28  

3.3.2 Fracture
3.3.3 Fatigue
3.3.4 Stress Corrosion Cracking of Steel
3.4 Non-Destructive Testing

4. Selection of Redesign Procedure
4.1 Design Strategy for Determining Redesign Process and Methods
4.2 Preparation
4.3 Clarifying Objectives
4.4 Setting Requirements
4.5 Establishing Functions
4.6 Convergence on Solution

5. Material Property Evaluation
5.1 Steel Shell Material Examination
5.2 Thermal Expansion of Refractory
5.3 Crushing Strength of Refractory
5.4 Young's Modulus of Refractory
5.5 Expansion and Shrinkage of Refractory

6. Self Weight Loading Effects
6.1 Bearing Positioning
6.2 Bending Analysis by Membrane Theory
6.3 Bending Analysis by Beam Theory
6.4 Finite Element Modelling of Self Weight

7. Thermal Loading Effects
7.1 Temperature Verification Through the Kiln
7.2 Wear Properties of Refractory
7.3 Theoretical Stresses due to Thermal Changes
7.4 Finite Element Modelling of Stresses due to Thermal Effects

8. Holographic Non-destructive Testing Quantified by Finite Element Modelling
8.1 Components used for Holographic Qualification
8.2 Finite Element Modelling of Flawed Cylinders
8.3 Mesh Generation and Refinement of FEM
8.4 Post Processing of FEM
1. Introduction

The central part of engineering design has to do with material and component behaviour. Engineering components are continually being developed to withstand increasingly severe conditions, in particular high temperatures, enabling better efficiency and performance. Therefore the study of design procedures for high temperature components is an essential engineering tool.

Design procedures for components would be straightforward, provided simple conditions prevailed. However, for real situations, components must perform satisfactorily under complex conditions. Furthermore, components and their material properties continually change due to extreme operating conditions with the potential for catastrophic failure. The safe and economical design of components therefore poses a major engineering problem. This is compounded by the importance of investigating redesigns and alterations of components already operational and in critical condition.

Design techniques have been extensively covered in the past by Pitts (1973), Polak (1976), Stotts (1968), Hubka (1982), Mayall (1979), French (1985), Pahl and Beitz (1984) to mention just a few. These, however, cover mainly design procedures for original, adaptive and variant design problems and do not suggest procedures for corrective redesign or design alterations. Furthermore, modern developments in computer analyses and non-destructive testing techniques have led to the opening of new avenues of investigation. New techniques can therefore be integrated with the traditional processes of design.

1.1 Problem Statement

There are many theoretical, practical and computational design techniques available to engineers for solving common problems. However, it is often difficult to choose the most appropriate techniques and integrate them correctly. It is unknown whether conventional design techniques are applicable to modern sophisticated designs, and if so, how accurate. There is a need to integrate the conventional techniques with new sophisticated techniques to solve complex problems accurately and efficiently. In order to do this, a design procedure is needed to guide the designer through the problem.

Furthermore redesigning or altering in situ engineering components is necessary to improve performance, extend the component's lifetime and to halt failure. The
component's condition, material properties and the effects of altering the original design are not normally known, therefore a redesign procedure for problematic in situ engineering components is needed. In order to achieve the above, a relevant case study must first be chosen. This must be a frequently occurring engineering problem which covers a large number of common problems, incorporating extreme and normal conditions, common and irregular shapes, loadings and materials, and a number of possible failure modes.

The vehicle selected as a case study is pre-reduction kilns. Pre-reduction kilns have long been used in the manufacturing of steel, and are the only pre-reducing structural components used in South Africa. Failure of these kilns, and other high temperature components such as refractory lined furnaces, are a common problem. These failures can be extremely dangerous, expensive to repair and can cause the halting of an entire engineering plant. Such failures have recently contributed to R17 million losses at Middelburg’s new chrome plant, and similarly caused continual shut-downs and repairs to the Highveld Steel and Vanadium plant. The production demands on the kilns have continually increased, extending the kilns beyond their design capabilities. In order to compensate for this, short term design alterations have been made. The problems have not been solved, but merely avoided for the present time. The normal course of repair and maintenance propose only short term solutions. There is a need for an efficient design procedure for investigating and solving such design problems thereby enabling effective redesigning.

Furthermore, Highveld Steel and Vanadium are continually expanding, demanding a greater number of pre-reduction kilns. The design of the new kilns is based on the existing kiln designs, with adaptations to avoid previously encountered problems. However, investigations into these adaptations are few and far between. The full effect of changing the original design to solve short term problems has not been realized.

The present rate of deterioration of the Highveld kilns suggests a short life of the existing kilns, and a reduced life of the recently designed kilns. An investigation into the kiln failure is therefore pertinent, not only for the particular problems, but also to establish techniques for design procedures, investigations and redesigns.
1.2 Objectives

The overall objective of this study is to review design procedures and related methodology for use in the redesign of components and systems subjected to high temperatures. The sub-objectives are the investigation of failure of components at high temperatures, the evaluation of component conditions after being subjected to service, the development of component analysis techniques and the finding of solutions to high temperature stress problems.

In order to meet these, an appropriate procedure for redesign is chosen and then applied to the case study. This incorporates an integration of common and newly available sophisticated design techniques focusing on components operating at high temperature which pose problems of greater complexity and of critical importance. The common techniques include material property evaluation, bending and thermal effects in cylinders, failure mode evaluations and life assessment. The sophisticated techniques include finite element methods and nondestructive testing techniques.

The objectives are achieved in the following way: Firstly the literature on which the procedure is based is surveyed. Highveld Steel and Vanadium pre-reduction kilns are then studied, investigating typical loadings and failure modes. Techniques for analysing and testing the component are then covered. A life assessment of the present kilns is done, and finally, conclusions and recommendations are given on the procedure and the case study.
2. Data Collected on Problem

Data covering aspects of pre-reduction kilns was collected and sorted in order to isolate information relevant to the objectives of this thesis. For this purpose, factual information gained from the Highveld Steel and Vanadium Company was used. This information ranged from kiln history to detailed problems encountered.

2.1 History of Rotary Kilns at Highveld

The steel mill pilot plant was built just west of Witbank between 1961 and 1963. The kilns are based on a Krupp-Renn process. Four kilns were built in 1968 following the success of the pilot plant. A fifth was built in 1972, a sixth in 1974, a seventh in 1976, and the last four in 1982. A new iron plant with two kilns has recently been completed but it is not yet in operation. The new kilns are imitations of the existing kilns.

2.2 The Kiln Operation and Process

The purpose of the rotary kiln is to preheat and pre-reduce iron ore. The ore is then fed to the electric smelting furnaces producing vanadium-rich pig iron.

The kilns must supply suitable feed for the smelting furnaces. Selection of the amount of input material is governed by the rate needed for the smelters. This means the kilns are not run to optimized kiln performance, but have to comply with the demands of the smelters. The input material, or charge, which consists of lump ore, coal, dolomite, and quartz, is weighed and fed into the concurrent flow kiln. An overall diagram of a kiln is shown in figure (2.1).

The charge (of bulk density 1760 kg/m\(^3\)) is first heated to reduction temperature in the pre-heating zone of the kiln. Here the charge is heated by hot gases (1100°C - 1300°C) from the coal burner by radiation, convection and by the kiln lining radiation. In this pre-heating zone the ore and coal are dried and the volatiles of the fresh coal are released. The dolomite is burnt at the end of the pre-heating zone.
2. Data Collected on Problem

The reduction temperature, which is approximately 1040°C, depends largely on the temperature at which fixed carbon of coal is converted to CO. The iron ore is reduced to sponge iron, maintaining its physical shape despite having been reduced by 50%. The reactivity of the coal also depends on the coal size. It is recommended by the operators that 10% to 30% of the total coal be fine coal in order to produce the necessary reactivity.

The kiln inlet has a central coal burner with an adjustable flame length and combustion intensity. The central burner is fed with coal fines of different sizes, causing combustion to occur in different areas, thereby avoiding high gas temperatures. Only part of the coal is gasified at the inlet, with the arising combustible being burnt downstream.

Air is injected through the shell of the kiln via submerged air injectors. This idea originated from the Acos Finos Piratini plant in Brazil and this allows an increase in throughput and heat transmission at lower gas temperatures. Combustion is controlled by further air inlet tubes in the reduction zone.
2.3 The Basic Kiln Design

The kiln consists of a cylindrical shell made of boiler plate steel with an inner lining of refractory castable as shown in figure (2.2). The steel shell is 60m long, 4m in diameter and 32mm thick. The refractory castable lining is 300mm thick and is plastered onto the inside of the shell.

![Diagram of kiln dimensions](image)

**Figure 2.2 Overall Dimensions of Rotary Kiln**

The kiln is supported by two roller stations consisting of two cast steel rollers each. The supports are positioned 12.4m from each end of the kiln. At the roller stations the kiln shell is reinforced to a thickness of 60mm under a running tyre of cast steel. The roller stations are supported on concrete pedestals arranged to allow the kiln to slope from the feed to the discharge end at an angle of 2 degrees. The high end roller station incorporates a thrust roller arrangement with two cast-steel rollers mounted in roller bearings and designed to run on the side face of the rear kiln tyre. Photographs of the kiln can be found in appendix (A).
The kiln is rotated by a main drive with a rotation variation of 0.4 to 0.2 rev/min. An emergency drive is used to rotate the kiln at 0.06 rev/min while off-line to prevent stagnant bending of the kiln.

The raw material is fed into the kiln via a double pendulum flap valve to prevent ingress of air into the kiln. The main combustion air is introduced via air pipes which are arranged along the kiln length and which project through the material bed inside the kiln. Each pipe is connected to an air fan mounted on the outside of the kiln enabling the temperature profile to be controlled.

The reduction plant is fully instrumented with each kiln being controlled separately.

2.4 Major Kiln Problems

There are two major problems found with the kiln. Firstly, refractory wears down and breaks away from the kiln shell causing thermal problems. Secondly, cracking occurs in the outer steel shell. It was not known whether the problems are related.

2.4.1 Refractory Decay

Over 50 different refractory types have been used since the commissioning of the first kilns. Initially, pre-cast bricks were used to line the kilns. The brick properties were good enough to withstand the harsh kiln conditions, but problems arose when one brick fell out. This would cause the surrounding bricks to follow, initiating a chain reaction. The thermal protection for the kiln shell would then be zero and the kiln would have to be taken off-line immediately without warning.

Due to the above factors and the improvement of refractory castable properties, refractory castables were experimented with, by replacing the bricks in order to overcome the problem of sudden overheating. Eventually refractory castables were used in all the kilns. Presently Hicast KL casable is being used with a few experimental variations.

The problem of refractory wear is caused by a combination of mechanical abrasion and slag attack. Slag attack is predominant in the hotter regions where the refractory reaches a high enough temperature to react with the charge. Slagging occurs above
2. Data Collected on Problem

1100°C. Penetration of the slagging occurs via the pore structure and interacting liquid phase. Slag penetration of 5mm normally occurs, indicating aggressive fluxing of the lining with rapid freezing within the lining. Highcast KL has 2% lime. Lime is the major fluxing agent and even though in small quantities, enables and encourages the occurrence of fluxing.

The castable takes on average fifty two weeks to thin down to an unacceptable thickness. This thickness is reached when the outside shell temperature exceeds 400°C. When the kiln is taken off-line, the kiln is rotated at 0.06rpm and allowed to cool by natural draught. After one and a half days, the kiln is cool enough to enter and repair. The refractory forms its own cylindrical structure inside the steel shell but is held to the steel with the help of short spikes welded to the shell. The repair takes on average twenty one days, after which the kiln is slowly heated over three and a half days from 25°C to 900°C, allowing the castable to dry. The kiln is then ready for production.

The cold crushing strength of Hicast KL is as good as fired brick but Hicast KL is not as well formed. Lime-bearing castables lose mechanical hardness at 1280°C, which is often exceeded in the kilns. Furthermore, the products based on the reaction between the lining and the charge are based on iron cordierite formation, which melts at temperatures as low as 1125°C.

2.4.2 Shell Cracking

Cracking of the kiln shell has occurred at the major stress areas: at the centre length of the kiln and at the inlet side riding ring, as shown in figure (2.3).

In some cases, circumferential cracks as long as 5m have formed through the shell thickness at the kiln centres and at the riding rings. These have been repaired by welding and by placing rectangular stiffeners across the crack.

In the kiln design, stresses due to self weight are largest at the centre of the kiln and at the riding rings. The temperature induced by the inlet flame is maximum at the inlet riding ring and considerably high at the kiln centre inducing thermal stresses. Due to the high temperature, these areas are most likely to lose castable and overheat, causing further stresses. There are major stress raisers such as air inlet pipes at the kiln centre.
and a thickness change at the riding rings. Welds are also present in these areas acting as defects and stress raiser.

![Diagram of kiln with cracks and welds](image)

**Figure 2.3 Positions of Cracks Found in Kiln**

### 2.5 Completed Tests on Kilns

A number of tests and investigations were completed by Highveld Steels in different areas to give further insight into the kiln problems.

#### 2.5.1 Process and Performance Tests

There are several factors affecting the hot metal production of the plant. An analysis of these parameters established how production could be increased in the future.

This investigation found the kiln performance (pre-reduction ability) depended on the temperature profile throughout the kiln, the size and density of the reducing agent, and
the distribution of combustion air in the kiln. The best pre-reduction performance was obtained when the temperature profile was maximum and stable, the feed rate at its slowest, and feed rate changes at a minimum.

2.5.2 Temperature Profile Tests

Quick-acting thermocouple tests were done on the kiln to establish the kiln cross sectional temperature profile. The thermocouples penetrated 15 cm and 30 cm into the kiln refractory.

The inner pre-heating zone temperature was found to be between 1150°C and 1200°C. The reduction zone temperature was found to be between 1040°C and 1050°C. The reduction zone gas temperature was found to be between 1360°C and 1400°C. The temperature difference between the gas and the charge was found to be on average 200°C.

It was found that 65% of the kiln was used for pre-heating. The filling degree (the percentage cross sectional area of the kiln that the charge occupies) was found to vary between 14% and 30% over the kiln length.

2.5.3 Refractory Investigation

Many refractory investigations have taken place due to the fast-developing demand for strong anti-fluxing castables. In 1982 tests were done on thirteen different castables to compare their different slag attacks. Slag attack was found to occur on all the castables, to a greater extent on some than others.

The latest break-through from Vereeniging Refractory Limited was the advancement from Verokast to Hicast castable. This improved the slag erosion by 20% by reducing the CaO content from 6% to 1.65%. This reduced the flux content from 30% to 8%. The mechanical strength at 1200°C improved from 35MPa to 100MPa. This is the presently used castable.

Attempts were then made to reduce the fluxing agents to negligible amounts. Tests were conducted on an Alucasi KL "no cement" castable. The CaO level of this castable is 0.1%, giving a significant improvement (20%) in slag resistance. This castable has
not yet been used by Highveld Steels. The future of this field could determine the life of the kilns as they are always being pushed beyond their limit.

2.6 Past Kiln Related Ventures

A number of design changes which have been undertaken on the kilns deserve mention.

2.6.1 Changing Refractory Thickness

An experiment is being undertaken by Highveld Steels to thicken the castable between the two riding rings to enable longer life between repairs. The consequences of such a change have not yet been quantified.

2.6.2 Blasting Out Refractory

An explosives company (Rapid Refractory Removal) introduced a time-saving technique of removing the refractory lining for repair.

The technique firstly involves drilling a number of holes through the kiln shell into the refractory. Bosses are then welded over the drill holes. Explosives are placed in the holes and progressively detonated, blasting out the refractory. The holes are then plugged for future use.

The blasting caused bosses to be blown off or cracked. In one case a 1.5m through crack appeared at the riding ring. The metallurgical tests indicated the cracking resulted from a high propagation rate fracture in a predominantly brittle mode. This was revealed by the presence of a chevron pattern on the fracture face as shown by the metal sample in figure (2.4). The fracture face is the left hand side of the sample.
2.6.3 Spraying Water on Kiln Shell

When the kiln shell outer temperature reaches 400°C, water is sprayed via overhead sprinklers onto the overheated region of the kiln. The outer temperature of the kiln shell is thus lowered, enabling operation to continue until such time that it is convenient to take the kiln off-line. This also allows for the time between repairs to be increased, thereby increasing productivity. The outside shell temperature is said to be reduced to around 90°C once the sprayers have been employed.

The temperature difference across the sprayed and unsprayed areas is on average 300°C. This area often coincides with the riding ring which is in a high stress area itself. Furthermore, the water is seen to be highly corrosive. The effect of spraying water on the kilns has not been investigated.

2.6.4 Welding up of Cracked Kilns

The above-mentioned cracks on the kiln shell are repaired by grinding and welding. There has been no investigation into why the cracking occurred except for the tests
2. Data Collected on Problem

mentioned already. If a large crack develops, arresting holes are drilled and stiffeners are placed over the crack.

In general, the welding of the original kiln and the repairs done to it are of very poor quality. The initiation of cracks is always found at a weld as expected. The effect of welding up cracks in the described manner has not been investigated, nor have alternatives been looked at.

2.6.5 Adding Gussets to Kiln Riding Rings

Gussets have been added on both sides of the inlet side riding ring of the kilns. These gussets connect the kiln shell to the reinforcing under the riding ring. They were introduced to arrest the cracking between the kiln and the riding ring reinforcement as described earlier. A diagram of the added gussets can be seen in figure (2.5) below.

![Figure 2.5 Riding Ring showing Addition of Gussets](image)

The gussets have acted as stiffeners and in some cases have also cracked. There was no investigation into the effect of introducing these gussets.
With the above collected data in chapter (2), a literature survey of design procedures for engineering components, with reference to the kiln case study, can commence.
3. Literature Survey

This chapter covers the literature "surveyed" during the development of the design procedure. Each section of this chapter begins with an overall view of the particular topic, which is then narrowed down to suit the case study. A different case study would merely redirect the emphasis towards that particular problem.

The survey firstly investigates design procedures (the mode or manner of conducting an investigation) which includes design processes (series of actions while designing) and design methods (the techniques used for designing). Secondly, material properties and behaviour is surveyed, with emphasis on the kiln materials. Thirdly, failure modes are surveyed with particular reference to the major stress and strain causes, and finally non-destructive techniques are surveyed.

3.1 Design Procedures

The activity we call "design" has a long history. Only recently have researchers begun to study the activity in order to understand it. The attempts to define the design activity have not proved entirely satisfactory. An example of one of the most commonly documented is the following used by ABET (Accreditation Board of Engineering Technology):

Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision making process in which the basic sciences, mathematics and engineering sciences are applied to convert resources optimally to meet a stated objective.

Design terminology has changed considerably within the past few years with different classifications of types of design. Pahl and Beitz (1984) group these under the following:

Original design: an original solution system for a system with the same, a similar or new task.

Adaptive design: adapting a known system for a changed task. Here original designs of parts or assemblies are often called for.
3. Literature Survey

Variant design: varying the size and/or arrangement of certain aspects of the chosen system with function and solution principle remaining unchanged.

In the past, good designs have been achieved by the "natural" designer or a chance encounter with the most appropriate solution to the problem. Modern technology has placed heavy responsibility on the designer, making the design procedures vital. This chapter offers an overview of design processes and methods.

3.1.1 Design Process

The literature contains descriptions of a number of "models" developed to help designers structure their approach to design. Some of these describe the sequence of activities that typically occur in designing, and other models attempt to prescribe a better or more appropriate pattern of activities.

a) Descriptive Models

Descriptive models usually emphasize the importance of generating a solution concept early in the process thus reflecting the "solution-focused" nature of design thinking. This initial solution "conjecture" is then subjected to analysis, evaluation, refinement and development. Cross (1991) suggests the simplest model of design process consisting of: generation of a concept, evaluation against goals, constraints and criteria of the design brief, and communication of the final design. French (1985) developed a more detailed model based on the following: analysis of the problem, conceptual design, embodiment of the scheme, and detailing.

Models of design process are often drawn in flow diagram form, with the development of the design proceeding from one stage to the next, but with feedback loops showing the iterative returns to earlier stages. Flowcharts of the above described two schemes are shown below. In French's model, the circles represent stages reached or outputs, and the rectangles represent activities or work in progress.
According to French the activities can be described as follows:

Analysis of problem: This includes a statement of the problem, limitations placed upon the solution and criterion of quality.
Conceptual design: This takes the problem statement and generates broad solutions to it in the form of schemes. This stage enables scope for design improvements and includes the most important decision making.

Embodiment of schemes: Here the schemes are worked up in greater detail and a final choice between them is made.

Detailing: Here small but essential points are decided upon.

b) Prescriptive Models

The activities of descriptive models are typical of conventional engineering design. Prescriptive models, however, are concerned with trying to persuade designers to adopt improved ways of investigating problems. They usually provide a more algorithmic systematic process to follow as opposed to the heuristic descriptive models. They emphasize the need for more analytical work to precede the generation of a solution. J.C. Jones (1984) defined the simplest systematic design methodology as follows:

Analysis: Listing of all design requirements and the reduction of these to a complete set of logically related performance specifications.

Synthesis: Finding possible solutions for each performance specification and building up complete designs with the fewest possible compromises.

Evaluation: Evaluating the accuracy with which alternative designs fulfil the performance, manufacture, and sale requirements before a final design is selected.

More detailed prescriptive models were developed by Archer (1984) and Pahl and Beitz (1984) in particular. The more complex models tend to obscure the general structure; however Pahl and Beitz retain clarity and provide a reasonably comprehensive model. They describe the following stages as follows:

Clarification of task: involves the collecting of information about the requirements to be embodied in the solution and also about the constraints.
Conceptual design: involves the establishment of function structures, the search for suitable solution principles and their combination into concept variants.

Embodiment design: involves determining the layout and component structure, developing a technical product or system, in accordance with technical and economic considerations.

Detail design: involves the arrangement, form, dimensions and surface properties of all the individual parts. This should include a recheck of all documents.

A flow diagram of the design process is shown in figure (3.2).

Considerable work on prescriptive types of models has been done in Germany. The Professional Engineering Body (VDI) has produced a number of "guidelines" including VDI 2222 "Systematic Approach to the Design of Technical Systems and Products". The VDI guidelines follow a general systematic process of firstly analysing and understanding the problem, then breaking this into sub-problems, finding suitable sub-solutions and combining these into an overall solution. Lera (1983) agreed with this approach finding "design problems were structured (analysed or decomposed) in terms of sub-problems".

A more radical model is suggested by March (1984). He argues that the two conventionally understood forms of reasoning, inductive and deductive, only apply logically to the evaluative and analytical types of activity in design. However, synthesis is particularly associated with design. He calls it "productive reasoning". His model for the design process is as follows: productive reasoning (requirements and presuppositions about the solutions), deduction (predict performance of the design), and induction (evaluate further possibilities).
3.1.2 Design Methods

Design methods consist of any techniques, aids or "tools" for designing. They represent a number of distinct kinds of activities that the designer might use and combine into an overall design process.
There have been many new methods developed to help overcome the difficulties of modern design problems. J.C. Jones (1981) compiled thirty five design methods. They are grouped under the following headings: Methods of exploring design situations, methods of searching for ideas, methods of exploring problem structures, and methods of evaluations. Some methods are formal versions of conventional procedures, some are applications of methods first developed in other fields, and some are new inventions. It was seen that different methods had different purposes and are relevant to different situations. Cross (1991) classified the general body of design methods into two broad groups, creative and rational methods.

a) Creative Methods

There are several design methods that are intended to help stimulate creative thinking. They work by trying to increase the flow of ideas by removing mental blocks or widening the area in which a search for a solution is made.

The first, and most widely used, is brainstorming. This generates a large number of ideas, most of which will be discarded, but a few followed up. The second is synectics, or the ability to see parallels or connections between apparently dissimilar topics. Here a solution is built from a combination and development of ideas. Finally, enlarging the search area, which can be done in a number of ways, some of which are: transforming the search from one area to another, random input of ideas, and asking "why" questions about the problem.

b) Rational Methods

Rational methods encourage a systematic approach to design, and often have similar aims to the creative methods. There is a wide range of rational design methods covering all aspects of the design process with different design methods being relevant to different stages in the design.

A number of rational design methods have been proposed. Among these are the systematic methods according to Hansen (1965) and Rodenacker (1970), the algorithmic methods according to Roth (1971) and Koller (1976), and the systems approach [Beitz 1971].

The above methods are strongly influenced by their authors' specialist fields. They nevertheless resemble one another closely. In all the methods the requirements are
abstracted for the purpose of arriving at generally valid functions or activities. The degree to which the various authors break down their functions, however, differs from case to case. All stress the importance of physical processes during the first phase. They also share the idea of step by step advance from a qualitative to a quantitative phase. Furthermore, all of them stipulate a deliberate variation and combination of solution elements of different complexities. All try to express the design process by simple rules or laws in algorithmic form.

Cross (1991) summarizes some of the design methods listing the major design stages and relevant design methods as follows:

<table>
<thead>
<tr>
<th>Design Stage</th>
<th>Design Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clarifying objectives</td>
<td>Objective tree</td>
</tr>
<tr>
<td>Establishing functions</td>
<td>Function analysis</td>
</tr>
<tr>
<td>Setting requirements</td>
<td>Performance specification</td>
</tr>
<tr>
<td>Generating alternatives</td>
<td>Morphological chart</td>
</tr>
<tr>
<td>Evaluating alternatives</td>
<td>Weighted objectives</td>
</tr>
<tr>
<td>Improving details</td>
<td>Value engineering</td>
</tr>
</tbody>
</table>

The first design method, the objective tree method, shows, in a diagrammatic form, the ways in which different objectives are related and the hierarchical pattern of objectives and sub-objectives. The functional analysis offers a means of considering essential functions and the level at which the problem is to be addressed by means of diagrammatic connecting boxes. The performance specification method defines the required performance needed and not the required product or components by means of an ordered list of demands and wishes of performance. The morphological chart method analyses the form that a product might take, widening the search for possible new solutions, by means of a chart which lists the features or functions together with the means by which they will be achieved. The weighted objectives method assesses and compares alternative designs by means of assigning different numerical weighting to the objectives and totaling for each design enabling a comparison to be made. The value engineering method focuses on functional values aiming to increase the difference between the cost and value of a product.

The selection and description of design process and methods relevant to the kiln redesign problem will be covered in chapter (4).
3.2 Material Properties

Knowledge of material properties is essential for any component investigation. The majority of design parameters depend on material properties in one form or another, as will be shown in later chapters. This chapter describes the materials and properties of the kiln case study, namely carbon steel and refractory castable.

3.2.1 Properties of Carbon Steel

The bulk of steel used in engineering is plain carbon steel. This incorporates "soft mild steel" through to "high carbon tool steel", carbon being of obvious importance to the material property. Similarly, different chemical elements and element quantities have marked effects on the steel properties. The material properties of steels can be found in various texts such as the "British Standards of Steels". The kiln steel is referenced as BS 1501-151 grad A steel, and has the following material properties:

- Yield Strength: 240 MPa
- Proof Stress: 202 MPa
- Young's Modulus: 207 GPa
- Poisson's Ratio: 0.29
- Density: 7810 kg/m³
- Thermal Expansion: 10.8E-6 /°C

A more comprehensive list of properties can be found in appendix (B).

Materials subjected to extreme in situ conditions can, and often do, undergo material property changes. Therefore it is important to note that the above-listed properties of the original steel may well have changed over time.

Heat treatment has the greatest effect on steel properties. The kiln case study is a typical heat problem, with material property changes likely to occur. Material re-evaluation should therefore be considered in the design procedure. It is, however, often difficult to re-evaluate material properties without damaging the component. Non-destructive testing is one method of doing so, and will be discussed in later chapters.
Heat treatment can have a number of effects on steel, depending on how it is implemented. The most notable effect is on the hardness of the steel. Hardening can be achieved by rapidly cooling a material from an elevated temperature. For plain carbon steel this temperature needs to be 750°C to enable the microstructure to transform from a soft chemical composite to a hard composite [Aitchinson 1953]. In many applications it is undesirable to have a completely hardened steel due to its brittle qualities. Softening (annealing) can also be achieved by heating the material above the transformation temperature, retaining that temperature for a prolonged period, and finally allowing it to cool over a protracted time. This softening has the effect of increasing the micro-structural grain size. In general, resistance to deformation increases as the micro-structure is made finer. Graphical representation of the above effects are shown in figure (3.3) [Sandor 1978]. This enables the hardness to be evaluated by inspecting the micro-structural grain size.

![Graph showing the effect of microstructure on strength and ductility](image.png)

**Figure 3.3** Effect of Microstructure on Strength and Ductility

Note should also be made of weldments which created heat affected zones. There is an increase in hardness due to recrystalization and a finer grain growth at the weldment [Pascoe 1972]. This can cause high stress concentration and brittle fracture.
Other effects on carbon steel properties will be discussed later in this chapter under the heading of failure modes. Failure modes incorporate effects such as creep, fatigue, fracture and environmental effects.

3.2.2 Properties of Refractory Concrete

Refractories are manufactured in many different forms for many different applications. The material properties of a particular refractory are best obtained from the supplier. Vereeniging Refractories submit properties with all their commercially used refractories, and the kiln refractory (Hicast KL) has the following properties:

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. service temperature</td>
<td>1650°C</td>
</tr>
<tr>
<td>Dried bulk density</td>
<td>2660 kg/m³</td>
</tr>
<tr>
<td>Cold crushing strength</td>
<td>85 MPa</td>
</tr>
<tr>
<td>Thermal conductivity</td>
<td>1.6 W/mK</td>
</tr>
<tr>
<td>Thermal expansion</td>
<td>7.5 E-6 /°C</td>
</tr>
</tbody>
</table>

The refractory has a lower density, thermal expansion and thermal conductivity than the steel, all of which are expected.

Further details can be found in appendix (B).

The supplied properties do not, however, cover all the properties necessary for the kiln analysis. Other relevant properties will be discussed below.

a) Hot and Cold Compressive Strength of Refractory Castable

Cold compressive strength given in the material property list above is the compressive stress which is used for theoretical calculations. The compressive strength does, however, change with respect to temperature, therefore hot compressive strength would be more appropriate. The reason for the use of cold compressive strength as opposed to hot compressive strength, is the difficulty of establishing the latter during testing. The use of the former is justified, however, if the cold crushing strength is found after the test specimen has been subjected to the operating temperatures [Petzold 1970]. The cold compressive strength listed above was established accordingly, and is considered valid.
The compressive strength is also affected by the loading rate. As the loading rate increases, so does the compressive strength [Avram et al. 1981]. Therefore a high loading rate is not detrimental to the refractory in compression as with most materials such as steels. This indicates that refractory failure is not due to high loading rates.

b) Expansion and Shrinkage of Refractory Castable

In refractory concretes, the expansion process due to temperature change is complicated by a superimposition of shrinkage of the binding agent (a reduction in volume when dried). The amount of shrinkage is determined by the refractory composition, and therefore the expansion and shrinkage process can be controlled and influenced by altering a fine fraction of the aggregate. This enables thermal expansion strains to be counteracted by shrinkage thereby reducing the thermal stresses. This idea of controlling the stresses is relevant to isolated experiments, but gives some insight into the interaction of the two phenomena [Petzold 1970].

c) Temperature Varying Elasticity of Refractory Castable

The elastic behaviour of materials has great significance for failure analyses. Nearly all analyses incorporate elastic behaviour, which is affected by many parameters. In the kiln case study context, temperature effect on elastic behaviour is of major significance. This dependence can be graphically described for high alumina cement and chamotte in figure (3.4) [Schneider and Mong 1958]. Hicast KL has a similar relationship between fired and unfired, although the minimum Young's Modulus is expected to be above 25GPa. This will be verified in chapter (5).
d) Softening Under Pressure of Refractory Castable

A property of particular practical importance is that of softening of concretes under pressure at high temperatures. A refractory concrete operating under such conditions will start to deform much earlier than would be expected. This makes test conditions more severe than operating conditions thus making calculated estimates safer. There is, unfortunately, no universal procedure for interpreting the softening behaviour of refractories. Tests on refractory castables and conventional refractories have been compared, however. The refractory castables were found to soften at temperatures as much as 300°C lower than conventional brick, with refractories softening in the region of 1500°C [Petzold 1970]. This enables stresses to be relieved under high stress.

e) Creep of Refractory Castable

Creep is the irreversible variation of shape under long-term loading. Few experimentations on refractories have been done in this field, and those undertaken
3. Literature Survey

have been over short periods. It has, however been shown to be of significant importance in many instances. There is a greater tendency to creep before firing of the refractory [Schneider and Mong 1958], as well as an increase in creep at elevated temperatures [Avram et al. 1981]. This means that stresses due to thermal expansion may be relieved during drying of the refractory.

The above material property investigation shows there are many uncertainties which are unavoidable. Material properties should therefore be used with care with a sensitivity study and accurate experimental data collection incorporated in the design procedure.

3.3 Failure Modes Related to the Steel Shell

When a component is subjected to loads, its response depends on the shape, the material, the environmental conditions and the manner of loading. A component may fail by excessive deflection, by yielding (at ordinary and elevated temperatures) and by fracture (sudden brittle fracture, progressive fracture or fatigue fracture and fracture with time at elevated temperatures). These failure modes are meaningful for simple components. However, under many different conditions, different failure modes are encountered. For example, in nuclear reactors cracks in pipe loops have been attributed to stress corrosion cracking [Clark and Gordon 1973].

A preliminary investigation of the kiln steel shell enabled the cause of failure to be narrowed down. Failure modes related to the kiln case study and selected for a further detailed survey are: creep, fatigue, fracture and stress corrosion cracking. The following chapters deals with each separately. This separation may be simplistic because of failures often occurring due to a combination of failure modes.

3.3.1 Creep

A component subjected to an increasing load will behave elastically up to a point where the load is large enough to cause permanent deformation. This is known as permanent set, where the component cannot recover to its original shape once the load is removed. The component is said to have behaved plastically [Hill 1964]. If temperatures are significantly higher than ambient, and typically above 0.4 of the
melting point, permanent deformation occurs at loads well below the expected yielding loads. This form of deformation accumulates with time until rupture can occur. This is known as creep.

Strain due to creep can be represented by a creep curve as in figure (3.5). This curve shows three well-defined regions: the primary, secondary and tertiary stages.

![Figure 3.5 Strain Accumulation during Creep Tests showing Primary, Secondary and Tertiary stages](image)

The earliest attempts at deriving constitutive relationships for creep assumed that creep deformation under constant uniaxial stress depended on stress, time and temperature. The most general creep law is therefore [Penny and Marriott 1971]:

$$
\varepsilon_{\text{creep}} = f(\sigma, t, T)
$$  \hspace{1cm} (3.1)
For simplicity, the variables are separated, allowing for individual analyses to be done. The separate stress and time functions have been accepted in most of the creep investigations and the creep strain becomes:

\[ \varepsilon_{\text{creep}} = f_1(\sigma) f_2(t) f_3(T) \] (3.2)

These functions will now be investigated in turn.

a) The Stress Function

The stress function \( f_1(\sigma) \) has been described in many ways using a number of different material constants, the most common of which is the Norton power law:

\[ f_1 = K \sigma^m \] (3.3)

\( K, m \) = material constants at a given temperature

This fits experimental data best at low stresses but approaches higher stress data within the limits of experimental scatter.

b) The Time Function

Many different time functions \( f_2(t) \) have been proposed, all of which are applicable only to certain ranges of test conditions. Furthermore, the introduction of stress and temperature parameters into the equation cannot be achieved without further complication. Therefore, used with care, one of many time functions can be of practical use. Some of the frequently documented functions are listed below.

\[ f_2 = (1 + bt^{1/3}) e^{kt} - 1 \] [Andrade]

\[ f_2 = F t^n \] (usually \( 1/3 < n < 1/2 \)) [Bailey]

\[ f_2 = G(1 - e^{-\delta t}) + H t \] [McVelly]
3. Literature Survey

\[ f_2 = \sum a_i t^{n_i} \]

[Graham and Walles]

\[ b, k, F, n, G, q, H, R, = \text{constants} \]

c) The Temperature Function

The temperature function \( f_3(T) \) has two effects on creep. It affects firstly the material constants (Young's Modulus, \( m \) and \( K \) in Norton's Law), and secondly, the material structure. For temperatures below 0.4 of the melting point (\( T_m \)), creep occurs primarily by slip similar to instantaneous plasticity. At these temperatures, dislocations encounter obstacles in the form of grain boundaries, causing strain hardening and a decrease in strain rates [Penny and Marriott 1971]. At temperatures above 0.4 \( T_m \), increased thermal activity allows dislocations to climb over obstacles. The most notable work in this field was done by Dorn (1955), who described temperature dependency in the form:

\[ f_3 = e^{-Q/RT} \]  

(3.5)

The above three functions, \( f_1 \), \( f_2 \) and \( f_3 \) can be incorporated into a single uniaxial creep equation, which is:

\[ \varepsilon_{\text{creep}} = K \ e^{-Q/RT} \ \sigma^m \ t^n \]  

(3.6)

This equation describes creep for uniaxial constant stress. The effect of variable stress and multi-axial stress will now be discussed.

d) Variable Stress

The above equates creep from data using constant stresses and temperatures. However, the majority of engineering problems exist with variable stress. The effect of variable loading under creep conditions is to produce complex deformation behaviour. There
are a number of theories describing variable stress creep. The most accepted are time hardening, strain hardening and mixed hardening. A more complete analysis can be found in Penny and Marriott (1971).

Mixed hardening proposes a compromise between strain and time hardening [Johnson et al 1963], giving better results over a range of materials. The mixed hardening hypothesis describes creep strain rate as a function of strain, time, and accumulated creep strain. Payne (1979) proposes the mixed hardening law of the form:

\[
\frac{d\varepsilon_c}{dt} = n K \varepsilon_0 e^{-Qu/T} \sigma^{am} (1 - \varepsilon_c)^{1 - a}
\]

(3.7)

e) Multi-Axial Stress Relationships

To complicate creep analysis further, engineering problems comprise multi-axial stress states. Therefore the above uniaxial constitutive relationships have to be extended to multi-axial relationships. This is accomplished by using an equivalent stress \( \sigma^* \) and an equivalent strain increment \( \varepsilon^* \) to represent the combination of a multi-axial stress system. The Von Mises yield criterion is usually used as an equivalent stress, being truer to fact and easier to use than the Tresca or similar criteria which are discontinuous in form.

As shown in the above chapter, creep analyses are extremely complex and contain a great number of uncertainties with the constitutive relationships often being purely empirical. Accurate data and parameters are therefore essential for creep analyses.

3.3.2 Fracture

Of the many ways in which a component can fail, the occurrence of fast, brittle fracture can have particularly disastrous consequences. In recent years, requirements for greater efficiency and performance have led to components operating near the mechanical limits of the materials. The research resulting from many costly failures has established the discipline of Fracture Mechanics. This has developed as a powerful tool for design, analysis of structures containing defects, material selection and failure analysis for critical components.
3. Literature Survey

The following chapters describe defects, material toughness, fracture mechanics models and factors which affect fracture.

a) Defects and Their Distribution

One of the fundamental principles of fracture mechanics is that all structures have flaws, whether they are metallurgical or microscopic, intrinsic or initiated in service. Also present in components are stress concentrating features in the form of rapid changes in section. These are often sites for the initiation of in-service cracks which may arise due to cyclically fluctuating loads (fatigue), corrosion or stress corrosion cracking.

Having established that flaws always exist in components, in order to quantitatively assess structural integrity, fracture mechanics analyses require some definition of the largest flaw that is present in a component or which can escape detection. Fracture mechanics needs limits for flaw sizes, from the initial flaw size to the flaw size at failure, in order to investigate the likelihood of failure. The probabilistic aspects of fracture mechanics have been extensively reviewed by Johnson (1978), who finds little experimental data is available with most estimates being based on experience and intuition. Furthermore, one of the most dangerous pitfalls in establishing the size of flaws using experimental techniques is the failure to recognise that the method, personnel and inspection environment must simulate the component service conditions.

b) Toughness and Fracture Toughness

A realistic assessment of the risk of fast fracture in structural components requires an evaluation of structural, material and operational parameters. The realistic incorporation of these can be done using large-scale tests under realistic conditions. However, primarily because of cost, research has been focused on small-scale laboratory tests. The best known and most widely accepted is the Charpy/Izod V-notch impact test which measures material "toughness". There are a number of limitations to the use of this parameter [Garrett 1979a]. The most significant of these is the inability to provide a quantitative parameter which can utilize flaw size determinations. Subsequent fracture toughness tests on tension or bend type specimens provide a quantitative measure of a material's resistance to cracking (i.e. its fracture toughness).
c) Linear Elastic Fracture Mechanics

Linear elastic fracture mechanics (LEFM) originated in 1920 when Griffith, using glass slides, investigated the relationship between fracture toughness, effective failure stress and flaw size. He found the fracture stress times the square root of the crack length at fracture was a constant. This interrelationship has come to be known as the "Triangle of Integrity".

This LEFM approach considers only elastic deformation of a solid and the local deformation to the extent of breaking the atomic bonds. Metals and alloys, however, exhibit more varied behaviour under applied stress and in particular by deforming plastically. Irwin and Orowan modified Griffith's equations independently to take into account for plastic work. The quantitative relationship pertinent to the triangle of integrity is expressed by a parameter known as the "stress intensity factor" (K) having dimensions of MPam$^{1/2}$. The relationship is:

$$K \propto \sigma \sqrt{\pi a}$$  \hspace{1cm} (3.8)

K = Stress intensity factor  
$\sigma$ = Total effective stress  
a = Crack length

When the value of K exceeds some limit, which is a property of the material at a specific temperature and material thickness, the crack becomes unstable. This limiting value is the critical stress intensity, or fracture toughness ($K_C$).

There are a number of factors which affect the fracture toughness of a material. These are: material thickness, yield strength, component and crack geometry, temperature and strain rate, and plasticity effects. These individual effects will now be discussed in the order above to give further insight into the fracture toughness parameter.

d) Material Thickness Effect on Fracture Toughness

The preceding discussion assumes the material is thin with plane stress conditions existing. Material thickness has a marked effect on fracture toughness as the component cross section changes from thin (plane stress) to thick (plane strain). In thin
specimens, there is negligible stress acting perpendicular to the surface causing formation of slant fracture which requires a significant amount of energy. Therefore the fracture toughness \((K_C)\) of thick sections of material is lower than that of thin sections. For thick sections, almost all the fracture surface is flat and \(K_C\) approaches an asymptotic minimum value \(K_{IC}\) as described by figure (3.6) [Garrett 1979a].

![Fracture Toughness vs. Thickness](image)

**Figure 3.6** Thickness Effect on Fracture Toughness showing Fracture Toughness Limit \((K_{IC})\)

It should be noted that if higher operating loads are required, using the common solution of increasing the thickness may result in a decrease in fracture toughness and therefore an increase in susceptibility to catastrophic failure.

e) **Yield Strength Effect on Fracture Toughness**

With increasing yield strength, a material's fracture toughness generally decreases. However, by using a higher quality steel, the fracture toughness \((K_{IC})\) value can be
increased even if the yield strength is increased. It is therefore important to select the material best suited for the particular application.

f) Component and Crack Geometry Effect on Fracture Toughness

The stress intensity factors discussed above apply to a straight planar through crack in an infinite sheet of material. Component and crack geometry affect the fracture toughness by altering the stress at and around the flaw. Different flaw shapes and sizes have been investigated for different materials [Bartholome 1974]. Stress patterns for complex geometries and flaw shapes are best evaluated using sophisticated analysis techniques (e.g. finite element methods). A geometric correction factor (Y) can be incorporated into the LEFM fracture toughness equation as follows:

\[ K = Y \sigma \sqrt{\pi a} \]  \hspace{1cm} (3.9)

g) Temperature and Strain Rate Effects on Fracture Mechanics

An increase in temperature causes the inherent toughness of most materials to increase. This temperature dependence is more marked for low strength structural steels, and only minor effects on high strength steels. Increasing load rate generally significantly decreases the fracture toughness of a material. The degree of change due to the above is dependent on the material, temperature and conditions. It is therefore important to use the appropriate fracture toughness relevant to the in situ temperature and strain rate.

h) Elastic Plastic Fracture

Materials, after deforming elastically, often yield plastically before failure. Therefore further modifications to the analysis above need to be made to accommodate elastic plastic fracture mechanics. There is a requirement to characterize the materials resistance to fracture, even when localized plasticity may be exhibited. To do so, an alternative to the linear elastic fracture parameter \( K_{IC} \) needs to be found. Two alternative toughness parameters have been proposed: the first is the critical value of "crack tip opening displacement" (COD), and the second is the J integral (a measure of the energy involved in opening and propagating a crack) [Knott 1973]. Only COD will
be discussed primarily because of its success in practical applications [Harrison et al 1978].

The concept of COD can be described as follows: As the load increases across a crack, plastic yielding occurs at the crack tip resulting in separation of the crack faces without any increase in the crack length. This separation of the two faces is known as the COD [Garrett 1979b]. The value of COD at the time of fracture is considered to be the measure of toughness of the material and is constant for given temperature, strain rate and plate thickness. During propagation of fracture, the only material controlling the fracture process is that situated around the crack tip. Therefore if the crack and material thickness of a test specimen and the component being investigation are the same, the COD for fracture should also be similar regardless of the component or structure's size. Methods for investigating COD have been compiled for general use [British Standards 1972] and its effectiveness has been substantiated by a large number of tests on different sized specimens [Knott 1973].

3.3.3 Fatigue

Fatigue results when the repeated application of stress, which in itself is insufficient to cause failure on a single application, causes cumulative damage. This failure mode leads to an estimated 95% of all engineering failures [Freudenthal 1970] and is observed in both crystalline and noncrystalline materials [Garrett 1979b]. Fatigue involves both initiation and propagation of cracks with irreversible plastic deformation playing a key role in each stage.

Fatigue has been under research for well over a hundred years yet failures continue to occur. One of the reasons for this are experimental fatigue data being inherently susceptible to wide scatter and the consequent difficulty in precisely modelling operating conditions over a component's entire life.

Generally, fatigue is a surface sensitive phenomenon with the initiation of a fatigue fracture associated with design details such as discontinuities (stress concentration features) or surface defects [Garrett 1979b]. Once initiated, cracks grow in three stages. Stage 1 is confined to a depth of only a few grain diameters into the material and is called "shear crack growth". This may be absent if a crack already exists. Stage 2 is fracture perpendicular to the tensile principle stress axis which often produces striation marks, each of which correspond to one fatigue cycle. Stage 3 is the
acceleration stage of fracture where striations course and often terminate leaving a course fracture surface.

a) Fatigue Lifetime Determination: The S-N Approach

The total lifetime determination of a component subjected to fatigue includes both initiation and propagation of flaws. It is conventional practice to measure fatigue strength in terms of the number of cycles to cause failure as a function of the peak applied stress or the stress amplitude (S-N). It must be noted that the wide scatter in experimental results is characteristic of fatigue and is not due to the inaccuracy of testing. The figure below shows the general form of a S-N curve with scatter [Gatto 1956]. This shows the amount of scatter more clearly than the conventional linear S-N curve plotted on a log scale. The fatigue limit is more clearly defined in some metals than others.

![Figure 3.7 S-N Curve showing Scatter for Aluminium alloy](image)

Because of the many factors affecting fatigue, it is often necessary to derive S-N curves for each design situation. However, in some cases such as steels, it is possible
to derive S-N curves from static tensile data without the need for dynamic fatigue tests [Wirsching and Kempert 1976]. This shows S-N curves that have an asymptotic minimum stress value, called the fatigue limit, which is constant after a large number of cycles. For steels having an ultimate tensile strength (UTS) of less than 1500 MPa, a fatigue limit of half the UTS is appropriate.

A further "fatigue strength reduction coefficient" can be applied to relate this value to real life design conditions to accommodate other factors affecting fatigue life. These include means stress, corrosion environment, surface finish, stress concentrations, size variations, frequency of loading, temperature, statistical scatter, fabrication and welding [Juvinall 1967]. Factors affecting fatigue will be discussed after the assessment of crack growth.

b) Crack Growth Assessment by Fracture Mechanics

The application of fracture mechanics to fatigue crack growth is well established [Wei 1978]. This assesses only the propagation stage of fatigue failure. The period of crack initiation is omitted with the presence of an initial crack in the component or early initiation being presumed. This approach therefore produces conservative life predictions. Since further crack growth is most likely to proceed from the highly stressed region at the crack tip, it is most appropriate to characterize the mechanical driving force in terms of the crack tip stress intensity factor (K). The most useful relationship is a single valued correlation in the nominally linear elastic range between the rate of fatigue crack growth (da/dN) and the stress intensity factor (K) [Wei 1978]:

\[
\frac{da}{dN} = F(K)
\]

(3.10)

\(F(K)\) = function of the stress intensity factor
\(a\) = length of crack
\(N\) = number of cycles

Two areas of material response are important to life predictions when using fracture mechanics. Firstly, fracture toughness, which is normally used to establish the condition for final failure (final crack length). Secondly, the kinetics of fatigue crack growth which governs the rate of degradation of the load bearing capacity of the component from an initial flaw size to the size at failure. Because of the complexity,
the environmental effects and the lack of understanding of the mechanism for fatigue, no kinematic relationships have been written which describe all aspects of fatigue fracture. It is therefore necessary to adopt a pragmatic empirical approach by using a piecewise power law as shown below [Wei 1978].

\[
\frac{da}{dN} = A_\alpha (K)_\alpha^{2n} \tag{3.11}
\]

\(\alpha\) = the interval for which the equation is fitted to the experimental data
\(A, n\) = empirical constants for that interval
\(K\) = stress intensity factor

Under conditions where the fracture mechanics approach applies, experimental results can be used to construct curves giving maximum allowable defect sizes for various applied stresses, component geometry and initial defect size.

Various attempts have been made to describe generalized "laws" for fatigue crack growth that incorporate the effects of variables such as stress ratio, frequency, etc. [Forman et al 1967, Schijve 1965]. These however have not met with complete success therefore the above relationship is the most generally used.

Design against fatigue may only be possible through an awareness of how fatigue strength can vary, coupled with full or semi scale simulation tests. The major variables affecting fatigue can be divided into the following categories: component conditions, loading conditions, and environmental conditions.

c) Effect of Component Conditions on Fatigue

Since fatigue cracking is a surface related phenomenon, it follows that fatigue strength is very dependent on surface conditions such as finish, hardness, residual stresses and stress concentrations. Surface hardening inhibits those micro-plastic deformation processes leading to crack initiation while residual compressive stresses offset the applied tensile stresses and prevent cracks opening. Stress concentrations are produced by any discontinuity in the component. The effect of a discontinuity is evaluated by comparing it's fatigue limit with that of a continuous component. This can also be
affected by section size and stress amplitude [Garrett 1979b], making the modelling of complex conditions extremely difficult without extensive laboratory testing.

d) Effect of Loading Conditions on Fatigue

Fatigue loading conditions include mean stress, frequency, variable and random loading and combined loading.

Design situations often involve a steady mean stress superimposed on an alternating stress. Fatigue behaviour is greatly affected by the value of the mean stress (static component), therefore the fatigue life can be expressed as a function of alternating and static stress. Various methods are available [Wirsching and Kempert 1976b], however, these have been found in practice to be applicable only to particular materials. The general uncertainty of such empirical relationships makes this effect extremely problematic to the designer.

Fatigue can take place over a wide range of frequencies. Over the range 1-200 Hz the bulk of experimental evidence shows the fatigue limit remains constant provided no heating or environmental attack is present [Frost et al 1974]. At higher frequencies the fatigue limit tends to increase. At very low frequencies environmental effects become important.

In practical situations in-service loading is not often of constant amplitude. Various models have attempted to predict fatigue behaviour under variable loading conditions, but only the Palmgren-Miner (PM) rule has been widely used. Even this model is considered inaccurate and in some situations dangerous. This rule models fatigue damage as cumulative in proportion to the magnitude of each cycle. There is at present little alternative to full scale testing under variable loading to simulate the exact component conditions.

In many components there may be two or three dimensional stress states. One design approach to incorporate this is based on the "distortion energy" theory of failure, which calculates an equivalent alternating stress for the use in a conventional S-N curve to predict fatigue failure. Furthermore, although linear elastic fracture mechanics predicts only stresses perpendicular to the crack are effectual to the crack, the other two principle stress have been reported to affect fatigue crack growth [Garrett et al 1979].
e) Environmental Effects

The two major environmental affects to be considered are temperature and corrosion.

The general effect of temperature is to shift the S-N curve parallel to the stress axis without changing the slope. There is an increase in susceptibility to brittle failure at lower temperatures with metals failing at shorter crack sizes. Conversely, at elevated temperatures, fatigue strength is generally reduced and factors which are considered unimportant at room temperatures, such as frequency or waveform shape, may be dominant [Allen and Forrest 1956]. 0.17 carbon steel shows fatigue stress decreasing by 30% over a temperature change of 600°C. Furthermore, elevated temperatures enhance oxidation and chemical attack. Protective surface treatments may result in considerable improvements. Fluctuating temperatures may also lead to thermal fatigue.

The influence of a corrosive environment causes a reduction in fatigue strength, and for steels, the fatigue limit in salt water is essentially eliminated [Garrett 1979b]. The simultaneous application of dynamic stress and corrosion leads to lower strength values than if considered separately. The effect of combined stress and corrosion is discussed in the following chapter.

3.3.4 Stress Corrosion Cracking of Steel

The definition of stress corrosion is the acceleration of the rate of corrosion by static stress [Uhlig 1948]. Stress corrosion cracking is the limiting case of spontaneous cracking that may result from combined stress and corrosion effects. Stress corrosion cracking is limited to failures in which no significant damage occurs in the absence of stress. There is an interaction between chemical reactions and mechanical forces. This causes a greater deterioration in mechanical properties due to the simultaneous action of static stress and exposure to a corrosive environment.

Stress corrosion cracking characteristics have been studied using various types of materials and alloys in different corrosive environments [Uhlig 1948, ASTM Symposium 1979 and 1980, Gibala 1984]. Of particular applicability to the case study is the corrosive potential of water on carbon steels. Uhlig's (1985) investigations showed high corrosion potential for high strength steels in water (yield strength >
.1250 MPa), and Schwietzer (1983) found steel is affected little by natural waters, stating that even large water tanks are often constructed of carbon steels. It is, however, generally agreed upon that carbon steel is corroded to a certain degree in a water-air environment. The basic characteristics of stress corrosion cracking are common to all material and environmental systems and will now be discussed.

a) Characteristics of Stress Corrosion Cracking

A review of the literature indicates that initial attack occurs even in the absence of stress, although this attack may be quite superficial. Most of the experimental evidence indicates that this initial attack governs whether the crack type is intergranular or transgranular. The difference between the two is shown in figure (3.8).

If initial localized corrosion fissures are intergranular, the subsequent cracking is intergranular. If the initial attack is in the body of the grain, transgranular cracking occurs.

Experimental evidence also indicates that variation in material composition, heat treatment, fabrication and mechanical processing affects the microstructure and consequently the stress corrosion cracking susceptibility. The importance of microstructure in the stress corrosion cracking process is indicated by many investigations. A few examples are the following: heat treatment of cold worked steel accelerates the corrosion rate [Uhlig and Revie 1985], an increase in carbon content
increases the corrosion rate [Uhlig and Revie 1985], nickel and chromium retard cracking whereas molybdenum enhances cracking in alloy steels [Congleton 1988]; Grain boundary precipitates and grain size greatly affects corrosion [Harwood 1956].

A further characteristic of stress corrosion cracking is related to stress. For stress corrosion cracking to occur, surface or subsurface *tensile* stress must be present. Stress corrosion cracking has never been observed to result from compressive stresses. As the magnitude of the tensile stress increases, the time until failure decreases [Harwood 1956].

![Figure 3.9 Effect of Applied Stress on Time to failure](image)

For many alloys, a *threshold* or *limiting* stress has been observed. That is a stress below which stress corrosion cracking does not occur. It has also been shown that the time for complete failure was the same whether the stress was applied from the outset or applied during the later stages of the test. The cracks grow in a plane perpendicular to the operative tensile stress with propagation being a discontinuous process.
b) Mechanisms of Stress Corrosion Cracking

A generalized mechanism which integrates and explains the above characteristics of stress corrosion cracking would be highly desirable. The first characterization was done by Dix et. al. (1944). This has not been altered significantly by subsequent research and has often been elaborated on. After an extensive literature survey, Harwood (1956) summarizes the stress corrosion cracking process in the following point form:

1) Localized electrochemical corrosion occurs along the narrow paths producing trench-like fissures. Fissures may occur along grain boundaries or in the body of the grain. More than one crevice may be produced, but one usually sharpens and deepens to a greater extent than the others. Crack coalescence may also play a role in failure where a merging of cracks may cause stagnant cracks to reanimate propagation [Parkins 1987].

2) As the fissure grows, a stress concentration is developed at its tip. At a sufficiently high stress, localized plastic deformation occurs at the tip of the fissure. This initiates a brittle crack.

3) Depending on the geometry of the component, rigidity of the loading fixture, operating conditions, and energy considerations inherent in brittle crack propagation, the crack may propagate through the entire component or stop after a finite distance.

4) Mechanical extension of the crevice exposes clean metallic surfaces, and the corrosive agent is immediately drawn into the crack by capillary action. A period of rapid corrosion follows.

5) Acceleration of corrosion rate, as a result of exposure of unfilmed metal surfaces to a corroding environment, rapidly decreases due to polarization and re-forming of films.

6) Conditions similar to stage 1) now prevail, and slow localized corrosion continues until the process is repeated.

Due to the number of affecting parameters and the complexity of the mechanism of failure, stress corrosion cracking has not been generally quantified. To obtain failure
and life prediction relationships, field experience and laboratory experimentation are essential. An example of such an investigation was done by Liu et. al. (1991).

With the knowledge of the stress corrosion mechanism, the failure mode can be recognised and prevention methods can be employed even though the improvements are not quantifiable.

c) Prevention of Stress Corrosion Cracking

There are a number of preventative methods for stress corrosion cracking. Methods relevant to the case study cover most of these methods and will be discussed below.

The most effective method of reducing susceptibility to stress corrosion cracking is to minimize the magnitude of the stresses. Mechanical and thermal stress relieving processes have been investigated and found to reduce thermal stresses to negligible levels [Porowski et. al. 1991]. The mechanical process introduces slight permanent contraction away from the corrosion endangered region, resulting in a compressive stress in the endangered region. The thermal process quenches the endangered region, and when normal temperatures are regained, high residual compressive stresses are present. Shot peening can also be used to introduce surface compressive stresses.

Cathodic protection is a frequently used protection method. This method uses an electric current to reduce the corrosion attack on a component. This was successfully illustrated by Parkins (1952) and is represented graphically in figure (3.10).

Coating or painting is the most widely used protection method. Many coatings are available, each having different properties for different service conditions. A further in-depth study of coatings can be found in Gabe (1983). A coating can be selected by referring to references such as the BS standards [BS5493 1977] or by consulting the supplier. The above preventative methods are, however, limited by the particular component and environmental conditions.

Again, as with fatigue fracture, stress corrosion cracking should be investigated with caution using accurate data. Stress corrosion cracking is extremely difficult to quantify, even in real time laboratory experiments. This failure mode should therefore be used as a description of the failure mechanism, and not as a quantitative analysis.
3.4 Non-Destructive Testing

Since people first realized the fallibility of engineering components, they have recognized a need to inspect these components in order to assess and prevent failure. A wide variety of test schemes exists, some destructive and others nondestructive.

Knowledge of a component's "real" material behaviour after ageing is obviously vital in optimizing its residual lifetime. Knowledge of "real" material properties and flaws enables rational procedures for maintenance and design changes to be established for components. This information would best be obtained without damaging the component or removing it from the work place. Non-destructive testing (NDT) is the most frequently used technique for finding in situ material properties and flaws.

The benefits of NDT are numerous and can be grouped under the following headings: increased productivity, increased serviceability, safety, and identification of properties. In particular, quality controlling of manufactured parts, reduction in frequency of
unscheduled maintenance, and extension of scheduled maintenance period is possible [Bray and Stanley 1989].

Many NDT tools are available, each being applicable to different situations. Bray and Stanley (1989) place the various nondestructive techniques (NDT) into two categories: active and passive. The active techniques are those where something is introduced into or onto the component. Passive techniques are those that monitor the component during a load environment or a proof cycle. Of these, the passive modern optical techniques have the ability to cover the most general criteria of usefulness.

Optical methods for the measurement of the displacements and strains in stressed bodies have long been used. Amongst the more recent of these is optical holography which was not practical until a light source with suitable coherent properties was available. The gas laser has these properties and at the University of Michigan (1965), Stetson and Powell discovered what is known as double exposure and time averaging holographic interferometry. This enables displacements of the order of small fractions of wavelength of light (typically $10^{-4}$ mm) to be easily detected.

Holographic methods have attracted much attention over the last decade as a tool for flaw detection which is truly nondestructive. The USA has used holographic techniques frequently in the aerospace, automotive and nuclear industries for the investigation of flaws in materials or the determination of manufacturing defects [McGonnagle 1961, 1984]. Development of this method has been prolonged due to defending established techniques, but the cost effectiveness of the former and the disadvantages of the latter are causing this to change.

Early applications of holographic techniques required laboratory environments, but were still used in some production-line inspections [SEM Symposium 1990]. Recent developments enable the use of pulsed holographic lasers to be used as a light source. Inspections of areas as big as 2m x 2m can be made instantly without stopping the working part under inspection. This technique also allows components to be inspected in remote areas at discrete times. A mobile, pulsed laser holocamera is shown in appendix (E.1).

The basic principles of holography and its application to nondestructive testing are now well established and have been widely used. The theory of holographic interferometry and its application will be discussed in a later chapter with specific reference to the case study.
4. Selection of Redesign Procedure

The demands placed on the designer in modern industry have made design procedures vital for efficient and good designing of engineering components. The area of design procedures is a relatively new field with limited research covering redesign of in situ components. Redesign procedures can not be unambiguously classified under the descriptive or prescriptive models discussed in the literature survey. Concepts from the two models can however, be used to form a new procedure.

For redesigning, the problems of the original design need to be isolated and understood before a solution concept can be created, therefore the redesign procedure follows a prescriptive method of design to begin with. This chapter firstly describes the redesign strategy employed in the redesign process. It then describes the stages and the methods used in the redesign procedure.

4.1 Design Strategy for Determining Redesign Process and Methods

A design strategy describes the general plan of action for a design and the sequence of particular activities in order to establish the design process and methods. To have a strategy is to be aware of where you are going and how you intend to get there.

Strategy styles range from "random search", a divergent lateral thinking design approach where no explicit design strategy is evident, to "prefabricated", a convergent linear thinking approach where a predictable sequence of well tried and tested actions is used [Cross 1989]. Most design projects require a strategy which lies between these two. Psychologists suggest that people tend towards one or the other "thinking styles" [Tovey 1986]. What is needed is a flexible, strategic approach to designing which identifies and fosters the right kind of thinking at the right time.

A design strategy should provide the designer with two things: a framework of intended actions within which to operate, and a management control function enabling adaptations to be made as more is learnt about the problem. Design techniques were chosen applicable to the redesign kiln problem. A morphological chart technique was not used because the problem of failure had to be investigated before solutions were foreseeable. The weighted objectives method was also not used because solutions were
restricted to corrective and preventative rather than new design solutions. This method could, however, be used at a later stage in the procedure if different redesigns were needed to be compared. An appropriate framework for the kiln case study is shown below. The reasons for selecting each stage will be discussed separately in the following chapters.

**Stages in the design Process**

1) Preparation
2) Clarifying Objectives
3) Setting Requirements
4) Establishing Functions
5) Convergence on Solution

### 4.2 Preparation

Redesign differs from normal design in that the design concept for redesigning has already been generated. Therefore the first stage in the redesign process is the gathering of information on the original design, the component history, problems encountered, and other relevant observations.

It is essential to gather as much information as possible on the design and problems. This enables a sound overall "picture" to be established before any ideas are incorporated into redesigning, ensuring no time and effort is wasted on inappropriate solutions. The data collected should cover the following: the history and development of the component, operating conditions, relationships with other components, initial design, problems encountered, tests already completed on the component, and any additional information which could be relevant.

### 4.3 Clarifying Objectives

The objectives of a design or redesign are often ill-defined with vague requirements. An important first step in designing is therefore to clarify the design objectives. These may alter, expand or contract as the problem becomes better understood and as a solution idea develops. It is important to have a statement of objectives that is clear and agreeable to the client and designer. The *objectives tree* offers a clear and useful format for such a statement. The objectives tree procedure is as follows:
1) Prepare a list of design objectives. These are taken from a design brief, from questions to the client and discussion with the design team.

2) Order the list into sets of higher level and lower level objectives. The expanded list of objectives and sub-objectives is grouped roughly into hierarchical levels.

3) Draw a diagrammatic tree of objectives, showing hierarchical relationships and interconnections. The branches in the tree represent relationships that suggest means of achieving objectives.

The following objectives tree was formed for the kiln problem:

![Objectives Tree for Kiln Problem](image)

**Figure 4.1 Objectives Tree for Kiln Problem**
4. Selection of Design Process and Methods

4.4 Setting Requirements

Design problems are always set within certain limits. These limits should not be defined too narrowly, eliminating acceptable solutions, or too widely, leading to inappropriate solutions. Setting requirements allows boundaries to the solution space to be established within which the designer must work. For the kiln problem, a performance specification method is used as opposed to a product specification method. The method emphasizes the performance that a design solution has to achieve and not any particular components which may be a means of achieving that solution. This suits the kiln problem because the components already exist.

The performance specification procedure is as follows:

1) Consider the different levels of generality of solutions that might be applicable.
2) Determine the level of generality at which to operate.
3) Identify the required performance attributes. Attributes should be stated in terms that are independent of any particular solution.
4) State precise performance requirements for each attribute. Wherever possible, specifications should be in quantified terms.

The highest level of generality for the kiln problem is the design of a new pre-reduction component and the lowest is the changing of the present design features. For finding an appropriate solution to the kiln problem, only features of the design need be studied. However, for the techniques of investigation, the highest level of generality can be used because there were no appropriate available techniques. With the level of generality established, performance attributes can be identified.

Performance attributes contain all the conditions that a design proposal should satisfy. It should also distinguish between demands and wishes. A list of performance attributes and precise requirements for the kiln is as follows:

<table>
<thead>
<tr>
<th>Demand or wish</th>
<th>Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prevent component failure</td>
<td>Keep performance and through-put of the kilns the same</td>
</tr>
<tr>
<td>D</td>
<td>Keep operating conditions as close to designed conditions as possible</td>
</tr>
<tr>
<td>W</td>
<td>Alterations done by non-experts</td>
</tr>
</tbody>
</table>
4. Selection of Design Process and Methods

Extend component life expectancy
- Reduce frequency of refractory relining
- Maximum frequency of maintenance equal to frequency of relining

Quantity of kilns to deal with
- Deal with 11 kilns which have been in use for 20 years
- Applicable to new kilns of the same design

Costs
- Keep costs to a minimum
- Preventative action rather than large scale alterations

Testing Requirements
- Able to analyse without removal from work place
- Able to test areas as large as the kiln diameter squared (2m x 2m)
- Able to analyse complex geometries
- Able to compare alternative designs

Time Constraints
- Complete investigation within 10 months

4.5 Establishing Functions

Design problems have many levels of detail and it is often necessary to consider the level at which a design problem is posed. This is best done by considering the essential functions that a solution type is required to satisfy rather than the potential type of solution. The essential functions are those that the investigation must satisfy. A functional analysis procedure is as follows:

1) Express the overall function for the design in terms of the conversion of inputs into outputs.
2) Break down the overall function into a set of essential sub-functions.
3) Draw a block diagram showing the interaction between sub-functions.
4) Draw the system boundary defining the functional limits of the investigation.
5) Search for appropriate means of performing the sub-functions and their interactions.

A functional analysis for redesigning is considerably different to normal designing in that the function of the component has already been established. However, the functions of the redesign procedure can be investigated using the same approach.

The overall function of the kiln investigation and the essential sub-functions with interactions are shown below. This is followed by an explanation of their selection.

Figure 4.2 Block Diagram of Kiln Redesign Functions
The first sub-problem is the verification of collected data and investigation into loadings. The procedure to this sub-problem begins with simple models and design techniques. This enables a base for the final sub-solution to be established. This was followed by an analysis of the simple models already investigated, using more sophisticated and accurate design techniques. This ensures no errors are incorporated in the latter techniques. At this stage in the design procedure, irrelevant loading types can be eliminated from the investigation. The sophisticated modelling technique can then concentrate on appropriate problem areas.

The design method for the first sub-problem, verifying data and investigating loadings, begins with the use of common theoretical models. These include beam theory, membrane theory, and thermo-elastic theory. These techniques are used only on simple models. For the detailed modelling, finite element methods are used. The method is applicable to almost all continuum or field problems, having a number of solution schemes. These include linear-elastic plane strain, plane stress, axisymmetric and shell problems to mention but a few. Non-linear problems such as plasticity and creep are also solvable. This covered all aspects of the kiln problem with the kiln geometry and conditions suiting the finite element method. Once finite element modelling was initially done, alterations were relatively simple, enabling redosigns to be easily assessed.

The second sub-problem is the investigation of failure of the kiln. This covers the failure modes suspected after the collection of data on the kiln. The procedure then eliminates irrelevant modes after the investigation of loading on the kiln. The remaining modes can later be further investigated during the design assessment.

The third sub-problem is the investigation of practical testing techniques, which was undertaken because of the uncertainties and unknown conditions involved in almost all in situ engineering components. There is a need to qualify and quantify material properties, loading conditions, and investigate failure using practical testing techniques to confirm the theoretical investigations. This can then be used in the design assessment stage of the procedure.

There was no design method available for solving the third sub-problem. A method for qualifying and quantifying material properties, loading conditions and failure of in situ engineering components was needed. Damage to the component was unacceptable, therefore the method had to be non-destructive. The method should also have the ability to analyse large components without removing them from the work place.
Holographic interferometry covered all the above criteria, but was only able to qualify, and not quantify, properties, loadings and failure areas. A design method of quantifying holographic interferometry is therefore developed and explained in a chapter (8).

4.6 Convergence on Solution

The design assessment stage of the procedure evaluates the three sub-solutions described in the previous chapter to enable problem causes to be established and a life assessment of the present design to be undertaken. The method of life assessment depends on the preceding investigations. Solutions to the kiln problems should be found by simple deduction from the three sub-solutions.

If applicable, redesigning using creative and rational methods follows. These redesigns can then be investigated and re-evaluated using sections of the above procedure. The redesigns and the present design can be compared using the weighted objectives method if the solution is not obvious.

The weighted objectives method follows the following procedure:

1) List the design objectives
2) Rank-order the list of objectives.
3) Assign relative weighting to the objectives using numerical values.
4) Establish performance parameters or utility scores for each of the objectives.
5) Calculate and compare the relative utility values of the alternative designs.

Finally, details of the investigation, solutions to the problems, and redesigns are communicated to whomever appropriate.

The redesign procedure covering the functions and methods for solving the kiln problem is described graphically below.
4. Selection of Design Process and Methods

Collect Data

Select Design Procedure and Methods

- Verify Data and Investigate Loadings
  - Simple Theoretical Modelling
  - Simple Modelling using Advanced Techniques
    - Compare above Results
      - Agree
      - Disagree
        - Eliminate Negligible Loadings
        - Eliminate Irrelevant Failure Modes
          - Analyse Isolated Areas
            - Assess Present Design and Problems
              - Life assessment of Design
                - Redesign if Applicable
                  - Details of Solutions and redesigns

Investigate Failure

- Investigate Practical Testing Techniques
  - Develop Practical Testing Technique to suit Problem
    - Use Developed Technique to Verify Theory
      - Analyse Isolated Areas
        - Assess Present Design and Problems
          - Life assessment of Design
            - Redesign if Applicable
              - Details of Solutions and redesigns

Figure 4.3 Overall Redesign Procedure for the Kiln Problem
5. Material Property Evaluation

For initial designs, materials are normally chosen during an integrated analysis of the design. During redesign or post operational analysis, the material properties should be re-evaluated. Material property evaluation is difficult without moving the material to a test laboratory with appropriate testing equipment. Therefore to test \textit{in situ} materials, a sample from the component needs to be taken. This damages the component. The component history is also usually complex, incorporating critical conditions. However, any properties that are possible to find, should be found to give further insight into the analysis. It must be noted that extrapolation from documented results, and even results from the case study, of material properties are subject to errors and uncertainties and should be used with caution.

For the kiln case study, the original steel and refractory properties are documented and described in appendix (B). The material properties of the steel are likely to differ from the original document properties due to the time elapsing since the beginning of operation. Therefore the properties of the steel need to be re-evaluated and the failure modes established. The refractory castable is replaced continually, allowing original material properties to be used. However, further refractory properties needed to be found for the kiln investigation. The evaluation of the steel and refractory properties and failure modes will now be investigated.

5.1 Steel Shell Material Examination

The \textit{in situ} material properties of the steel could not be found without removing a sample from the component thereby damaging the structure. A number of material samples of the kiln were extracted from the kiln shell by cutting out steel samples. These samples were taken from areas away from the cracks in the kilns. Tests conducted on the yield strength, tensile strength, percent elongation and Charpy impact, revealed there had been no loss in mechanical properties away from the cracked regions. These samples were not taken in critical stress or high temperature areas, and do not give a true indication of the entire kiln condition.

Metallurgical examinations of cracked areas were done using a sample of the kiln shell cut away near a crack. A similar crack shown in figure (5.1) occurred in three other kilns in the same area. Photograph a) shows the area of cracking. Photograph b) shows the unetched root of the crack and c) shows the etched root of the crack.
a) Crack at riding ring showing weld beads and weld craters

b) Unetched root of crack showing branching and corrosion product within crack
5. Material Property Evaluation

The chemical composition was examined and found to be similar to the BS specification (see appendix (B)). The sample was severely eroded with a woody fracture face indicating a slow propagating stress corrosion failure. A metallurgical examination indicated stress corrosion. No trace of as-rolled grain structure was found, indicating the metal had been overheated well above 860°C and allowed to cool at a critical rate. This structure has inferior mechanical properties.

A Vicker's hardness test gave average values of 30% lower than normal. This hardness was considered to be very low, indicating overheating. The crack was seen to propagate in stages and not by sudden catastrophic failure. This again indicates stress corrosion cracking as being the initial cause of failure with further propagation being attributed to a fatigue effect. The normal operating temperature of the kiln was kept...
below 0.4 of the steel melting temperature therefore the failure mode did not incorporate creep.

5.2 Thermal Expansion of Refractory

The thermal expansion of the Hicast KL refractory was only documented at one temperature (1000°C) in the material specifications given by the supplier. The thermal expansion was not known at other temperatures. The effect of a varied thermal expansion with respect to temperature, would be to change the stresses induced by thermal changes. This change is only relevant if the thermal expansion does change with respect to temperature.

A number of Hicast refractories were subjected to thermal expansion tests by Vereeniging Refractories, the results of which are described in figure (5.2). It can be seen that all the refractories expanded linearly and have the expected gradient, therefore the use of a single value of thermal expansion over the entire temperature range is valid.

![Figure 5.2 Effect of Temperature on Thermal Expansion of Hicast Refractories](image-url)
5.3 Crushing Strength of Refractory

The Verref Division of Amcoal conducted further experiments to find the typical mechanical strength of Hicast refractories. These were compared to conventional refractories. The results showed the hot strength of Hicast refractory was similar to the cold strength, increasing slightly with temperature. It was also shown that the cold crushing strength of the Hicast refractory was considerably higher than the conventional refractory. The results are graphically represented in figure (5.3). This shows the cold crushing strength of Hicast refractory to be above 85MPa.

![Figure 5.3 Effect of Temperature on Cold Crushing Strength of Hicast and Conventional Refractories](image-url)

5.4 Young's Modulus of Refractory

Surprisingly, the Young's Modulus (E) of the Hicast KL refractory was undocumented. Vereeniging Refractories conducted laboratory tests on dried Hicast KL, finding a Young's Modulus of 53GPa at room temperature. This was higher than
the expected 25-30GPa, but was accepted on the grounds of Hicast being the most recently developed castable. It should be kept in mind that at temperatures above 300°C the Young’s Modulus can decrease by more than a half for dried refractory. This means the refractories Young’s Modulus can be regarded as being between 25GPa and 53GPa. This only affects the refractory stresses and not the strains, therefore the steel stresses and strains are similarly unaffected.

5.5 Expansion and Shrinkage of Refractory

Tests have been done by CSIR (Pretoria) using a dialatometer to monitor the expansion and shrinkage of Hicast refractory. The results showed that when the refractory is dried, thermal expansion is countered by shrinkage up to a temperature of 1000°C. Above this temperature little shrinkage is encountered. Plasticity occurs at temperatures above 1300°C, causing a glassy phase tempering effect. Poisson’s ratio was found to be 0.25 which was only slightly smaller than expected.

This compensation of thermal expansion via shrinkage was expected and will reduce the thermal stresses and strains while the kiln refractory is drying and heating up from ambient temperatures after relining.

With the material properties and failure modes established, the effects of loading can be investigated.
6. Self Weight Loading Effects

There are two loading types on the kiln. These are loading due to self weight (discussed in this chapter) and loading due to thermal changes (discussed in the following chapter). These will be analyzed separately to determine the relative effect of each. If one has a far greater effect causing greater stresses and strains, the other can be assumed to be negligible, thereby simplifying the problem.

The self weight effect incorporates the stresses and strains induced by gravitational loading. Firstly, the initial design of the kiln will be looked at using simple beam theory. This incorporates criticism of the positioning of the support bearings. Secondly, the effect of self weight on a simplified design model of the existing design is established using membrane and beam theory. Finally, finite element models are developed, starting with the previously studied model, and ending with a more intricate and defined model. The FEM will be able to take geometric discontinuities and material changes into account. The membrane and beam theory models enable verification of the first finite element models. Thereafter, a progressive approach allows the effect of adding different parameters to be quantified. The general effect of each added parameter should be intrinsically known, therefore the outcome of the FEM can be accepted or rejected.

6.1 Bearing Positioning

Simple beam theory can be used to calculate the optimum position for the bearing supports. This minimises the stresses and strains induced by self weight. The original design is ignored but will be compared with the optimum positioning after the analysis.

To minimise the stresses and strains, the bearing supports need to carry equal loads. Therefore the supports need to be placed equal distances from the ends. Figure (6.1) describes three different positions of the supports with corresponding bending moment diagrams. Two of these are extremes, a) and b). Between these two there will be a position for the supports at distance x from the ends which minimises the moment and thereby the stresses, c).
6. Self Weight Loading Effects

From the moment diagrams, it can be seen that this minimum occurs when the moment at the centre of the kiln is equal to the moments at the supports. Therefore to find the
distance $x$, the moment at the supports and at the centre must be expressed as a function of $x$.

Therefore: moment at centre = moment at support

$$\frac{wx^2}{2} = \frac{wl^2}{8} + \frac{wl^2}{4} - \frac{wx}{2} \quad (6.1)$$

Therefore solving for $x = 0.207 \, l$ or $-1.207 \, l$.
The negative value can be ignored.

For a kiln of length 60 m, the supports should be positioned 12.42 m from the ends. The original design has the supports positioned 12.4 m from the ends of the kiln, which is correct.

### 6.2 Bending Analysis by Membrane Theory

Shell theory significantly simplifies 3-D stress and strain calculations and has been used in many structural applications. This has been studied extensively by Timoshenko (1959), with many others following and using his derived principles [Sih 1977, Gibson 1980, Calladine 1983, Ugural 1981, Gioncu 1979, Donnell 1976]. This theory is valid only when a number of criteria are fulfilled. These are:

1) The thickness of the structure is considerably smaller than the other dimensions (thickness to smaller span $< 1/20$).
2) The deflections are small compared to the thickness.
3) The plane sections through the shell are taken normal to the mid-face and remain normal after bending.
4) The radial stress is zero.

To describe the shape of a shell, the geometry of the mid-face of the shell and the thickness of the shell need to be known. The analysis of shell structures often embraces two distinct theories: firstly, the **direct membrane theory** where the structure is incapable of conveying moments or shear forces, secondly the **bending theory** which enables the effects of bending to be estimated. The bending theory generally comprises a direct membrane solution, corrected in those areas in which discontinuity effects are
pronounced. The complete shell membrane theory is mathematically intricate with the first solution involving shell bending stresses dating back to only 1920.

The equilibrium equations for cylindrical shells, when neglecting bending action, can be written as [Timoshenko 1959]:

\[
\frac{N_\theta}{r} = p \tag{6.2a}
\]

\[
\frac{1}{r} \frac{\partial N_\theta}{\partial \theta} + \frac{\partial N_{x\theta}}{\partial x} = -q_\theta \tag{6.2b}
\]

\[
\frac{1}{r} \frac{\partial N_x}{\partial \theta} + \frac{\partial N_{x\theta}}{\partial x} = -q_x \tag{6.2c}
\]

- \(p\) = normal loading Component
- \(q\) = tangential Loading
- \(r\) = radius
- \(N\) = force per unit length

In order to solve equations (6.2) for particular conditions, \(N_\theta\), \(N_{x\theta}\), and \(N_x\) need to be determined. From equation (6.2a), \(N_\theta\) can be found if the radius and inner pressure are known. \(N_\theta\) can then be substituted into the second of equations (6.2) to obtain \(N_{x\theta}\). Finally \(N_x\) can be solved from boundary conditions.

A horizontal uniform circular cylindrical shell loaded vertically by self weight, has particular relevance to the kiln case study, with the solution to the forces in equations (6.2) being as follows:

\[
N_\theta = - rf \cos(\Theta)
\]

\[
N_{x\theta} = - 2f \sin(\Theta)
\]
In considering the mid-surface unit deformation, the change of curvature and the mid-face twist, the compound membrane stresses produced by forces and moments for a shell are [Timoshenko 1959]:

\[\sigma_x = \frac{N_x}{t} - \frac{12 M_x z}{t^3}\]

\[\sigma_y = \frac{N_y}{t} - \frac{12 M_y z}{t^3}\]

\[\tau_{xy} = \frac{N_{xy}}{t} - \frac{12 M_{xy} z}{t^3}\]

The first term in the above three equations describes the direct membrane stress and the second term describes the bending stress.

For thin shells with no major geometric discontinuities, direct membrane theory, ignoring the bending effect, is sufficiently accurate. This enables the working stress to be calculated from equation (6.5) below.
The above equations enable the total stresses of a cantilever shell under self weight loading to be calculated. Because the moment at the supports and the kiln centre are equal (from chapter (6.1)), only the effect due to self weight at either the centre or the supports need be analysed. There is a dramatic thickness change at the supports, and therefore little change in curvature and deflection occurs. The assumption of the kiln being a cantilever from the support onwards can therefore be made for a first approximation.

Substituting equation (6.3) into equation (6.5) enables the stresses due to self weight of a cantilever to be found by the equation below.

\[
\sigma_x = \frac{x^2 f \cos(\Theta)}{r t}
\]

\(\sigma\) is max when \(\Theta = 0\) and \(x = 1\)

\[
\sigma_{x,\text{max}} = \frac{l^2 f}{r t}
\]

\[
\therefore \sigma_{x,\text{max}} = \frac{l^2 (\rho g t)}{r t}
\]

\[
\therefore \sigma_{x,\text{max}} = \frac{l^2 \rho g}{r}
\]

\(l = \) cantilever length
\(\rho = \) steel density
\(g = \) gravitational constant
\(r = \) radius
\(t = \) thickness
\(f = \) weight per unit area
This enabled the stresses due to the self weight of the kiln acting as a cantilever to be calculated. The results are tabulated together with the FEM results in table (6.1).

6.3 Bending Analysis by Beam Theory

A simpler method of finding self weight stresses is by beam bending analysis. In this analysis one dimension of the component is significantly larger than the other two, and is usually loaded in the direction normal to the longitudinal axis. Beam problems have been covered extensively in the past, especially in the design of structures [Shigley 1986].

Normal stress due to bending of beams can be described by the well-known flexure formula applicable to straight beams.

\[
\sigma = \frac{M y}{I} \quad (6.7)
\]

\( \sigma \) = Bending stress  
\( y \) = Distance from the neutral axis  
\( M \) = Bending Moment  
\( I \) = Second Moment of Area

Strain energy methods are also used for calculating beam deflections of straight and bent beams. Of the many approaches available, Castigliano's Second theorem is the most commonly used, however the above approach proved sufficient.

Beam theory was also used to analyse the same simple cantilever as the membrane theory. Beam theory produces a similar expression to membrane theory but includes thickness as a variable.

Doing the following substitution:
6. Self Weight Loading Effects

Substituting $M = \frac{f l^2}{2}$

and $I = \frac{\pi}{64} (r^4 - (r-t)^4)$

Into $\sigma = \frac{My}{I}$

Produces

$$\sigma = \frac{4rt (r-t/2)}{r^4 - (r-t)^4} l^2 \rho g$$

(6.8)

When the thickness is considerably smaller than the radius, the expression reduces to the membrane theory expression.

For $t << r$ $\sigma = \frac{1}{r} l^2 \rho g$

Equation (6.8) can be used to calculate the stresses due to the kiln self weight acting as a cantilever. The results are tabulated together with the FEM results in table (6.1).

6.4 Finite Element Modelling of Self Weight

The ABAQUS finite element package was used for the finite element modelling. Shell elements were used to model the self weight loading effect of the kiln case study. Axisymmetric elements were inapplicable because of the non-axisymmetric gravitational loading. The shell model covered all aspects of the model criteria and proved flexible enough to facilitate alterations. Included in the shell model were options to incorporate composite materials or layered composites. This was convenient for incorporating the refractory into the steel shell model.

The first model simulated the model investigated by membrane and beam theory. This simple cantilever loaded by self weight was modeled using an unrefined mesh of shell elements which can be seen in appendix (C). The results could then be compared to the membrane theory results before further intricate models were attempted. The second model incorporated the refractory into the first model by using composite shell elements. The third model incorporated the charge flowing in the kiln into the second
model. The fourth model was a cylinder supported at both ends using a similar mesh and element size as the previous models. The final model was the entire kiln including supports and riding rings. A mesh of only a quarter of the kiln needed to be modeled because of the kiln's symmetry. Shell elements facilitated the attachment of two cylinders enabling the riding ring to be modeled as a shell around the kiln shell. Mesh refinement was done on the first model investigated in order to check convergence of the results.

The stress results are shown in table (6.1). The correlation between the membrane theory, beam theory and the finite element model results are good, with the membrane and beam theory results being slightly lower than the finite element results. The models showed an increase in stresses due to addition of new material. The finite element models developed from case 1) to 5) and are described below.

Case 1) The kiln is modelled as a cantilever shell, of length 12.4m and outer diameter of 4m. Only the steel is considered.

Case 2) The refractory is added to case 1).

Case 3) The charge flowing in the kiln is added to case 2)

Case 4) The kiln shell (with steel, refractory and charge) between the two riding rings is modelled. The length is 36m and the outer diameter is 4m. The shell ends are allowed to expand axially but are restrained in all other directions.

Case 5) The entire kiln with riding rings is modeled. The length is 60m and the outer diameter is 4m. The supports simulate the bearing that the riding rings move on.

Mises stress contours plotted on the models for cases 1) and 5) can be found in appendix (C).
6. Self Weight Loading Effects

<table>
<thead>
<tr>
<th>Case</th>
<th>Steel Thickness mm</th>
<th>Refractory Thickness mm</th>
<th>Charge Depth %</th>
<th>Membrane Theory Max Stress MPa</th>
<th>Beam Theory Max Stress MPa</th>
<th>FEM Max Stress MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32</td>
<td>0</td>
<td>0</td>
<td>5.9</td>
<td>5.9</td>
<td>6.2</td>
</tr>
<tr>
<td>2</td>
<td>32</td>
<td>300</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>10.5</td>
</tr>
<tr>
<td>3</td>
<td>32</td>
<td>300</td>
<td>35</td>
<td>-</td>
<td>-</td>
<td>17.5</td>
</tr>
<tr>
<td>4</td>
<td>32</td>
<td>300</td>
<td>35</td>
<td>-</td>
<td>-</td>
<td>20.7</td>
</tr>
<tr>
<td>5</td>
<td>32</td>
<td>300</td>
<td>35</td>
<td>-</td>
<td>-</td>
<td>26.2</td>
</tr>
</tbody>
</table>

Table 6.1 Steel Stresses Induced by kiln self weight

All the results are well below the yield stresses for the steel and refractory. The steel stresses are also below the fatigue limit of the carbon steel [Aitchinson 1953], therefore, fatigue would not occur only due to self weight loading. The final model of the entire kiln showed an expected concentration of stress at the points of contact with the supports, but this still remained relatively low compared to the yield stress.

The progressive analysis undertaken enabled the effects of adding different materials to be seen. It also enabled progressive confirmation of the FEM being analysed. It was found vital to build up from a simplistic finite element model to the final model, rather than attempt to construct the final model from scratch. With this progressive approach, modelling problems were encountered one at a time. The next model could be analysed once confidence in the previous model was attained.

The stresses found due to the kiln self weight in this chapter can be compared with the stresses found due to thermal stresses in the following chapter.
7. Thermal Loading Effects

Thermal effect incorporates the stresses and strains induced by a thermal change causing thermal expansion. Again a theoretical approach is employed initially to enable a general overview of the problem to be established.

Firstly, the temperature through the kiln will be verified. This will establish whether the parameters and boundary conditions given are correct and comprehensive. Secondly, the unknown parameter of refractory wear rate will be theoretically established. This is not a monitored parameter on the kiln site, and is important to the thermal analysis. Thirdly, the theoretical stresses due to thermal changes will be established. Finally, stresses will be established using the finite element analyses. A comparison of the theory and FEM will enable verification of the initial model, which can then be used as a basis for following models. Again a progressive modelling approach will be undertaken to investigate the effect of different parameters in turn. The effect due to thermal loading will then be comparable to the effects due to self weight loading. If one of the two is relatively small, it can be assumed to be negligible. The analysis can then continue by analysing the problem areas in further detail considering only the important loadings.

7.1 Temperature Verification Through the Kiln

In order to use thermo-elastic equations, thermal boundary conditions have to be established. This is done using thermodynamic and heat transfer principles of conduction, convection and radiation. The integration of these principles leads to solving of many practical problems.

The basic relations for heat transfer through a constant area in a unit time are [Holman 1989]:

\[ q = kA \frac{\partial T}{\partial x} \]  \hspace{1cm} (7.1a)

Conduction

\[ q = hA(T_w - T_\infty) \]  \hspace{1cm} (7.1b)

Convection
7. Thermal Loading Effects

Radiation \[ q = \sigma \varepsilon AT^4 \] (7.1c)

- \( A = \) Surface area
- \( h = \) Heat transfer coefficient
- \( k = \) Thermal conductivity
- \( \sigma = \) Stephan Boltzmann constant (5.669E-8 W/m²K⁴)
- \( \varepsilon = \) Emissivity
- \( T_w = \) Temperature at convection surface
- \( T_\infty = \) Ambient temperature

These can all be converted to cylindrical co-ordinates enabling more specific problems to be analysed easily in greater depth.

Experimental data for free convection problems appear in a number of references, with some conflicting results. Holman (1989), however, gives these results in a summary form for calculation purposes. In particular, for the case study, the heat transfer coefficient of free convection from a horizontal cylinder to air at atmospheric pressure can be calculated from the following empirical equation:

\[ h = 1.32 \left( \frac{\Delta T}{d} \right)^{1/4} \] (7.2)

The basic thermal boundary conditions of the kiln at the beginning of operation are the inner and outer temperatures. The inner kiln temperature is measured continually during operation via thermocouples and is 1150°C during normal operation. The outer temperature is only measured once the shell is suspected of overheating, and the initial outer temperature is estimated by the kiln operators as 100°C.

To verify these temperatures, a thermal analysis of the kiln cross section has to be done. This is accomplished by equating the heat transfer through the kiln with the heat loss from the shell surface to the atmosphere.
The temperature through the steel shell is assumed to be constant because of steel thermal conductivity being considerably larger than the refractory conductivity. Thermal uniformity along the axis of the kiln is also assumed.

Using equations (7.1), the thermal convection coefficient \( h \) for the kiln can be found.

\[
\frac{k \sqrt{2\pi l (T_1 - T_3)}}{\ln \frac{R_2}{R_1}} = h 2 \pi l R_3 (T_3 - T_\infty) + 2 \pi l R_3 \sigma \epsilon (T_3^4 - T_\infty^4)
\]  

(7.3)

This can be compared with the coefficient found from the empirical relation for a free convection from a horizontal cylinder using equation (7.2).

The original variables given for the above two equations are:

- Inner temperature of kiln: 1150°C
- Outer temperature of kiln: 100°C
- Refractory thermal conductivity: 1.6W/mK
- Refractory thickness: 0.3m
- Emissivity: 0.8

The two methods of calculating thermal coefficient should produce the same value for \( h \). However, using the above given conditions, this does not prove true. The effect on the two equations (7.2) and (7.3) of changing each variable is therefore desirable. This will give an indication of which variable is incorrect. Variations of the variables and their results can be seen in table (7.1) below.
### Table 7.1 Results of different Thermal Boundary conditions giving comparison of two calculated thermal convection coefficients

<table>
<thead>
<tr>
<th>Changing Variable</th>
<th>Calculated $h$ (W/m$^2$°C) from equation (7.3)</th>
<th>Calculated $h$ (W/m$^2$°C) from equation (7.2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Inner Temp. (°C)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>51.19</td>
<td>2.75</td>
</tr>
<tr>
<td>1150</td>
<td>60.87</td>
<td>2.75</td>
</tr>
<tr>
<td>1300</td>
<td>70.54</td>
<td>2.75</td>
</tr>
<tr>
<td><strong>Outer Temp. (°C)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50</td>
<td>207.45</td>
<td>2.99</td>
</tr>
<tr>
<td>100</td>
<td>60.87</td>
<td>2.75</td>
</tr>
<tr>
<td>265</td>
<td>3.67</td>
<td>3.67</td>
</tr>
<tr>
<td><strong>Refractory Thermal Conductivity (W/mK)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>35.47</td>
<td>2.75</td>
</tr>
<tr>
<td>1.6</td>
<td>60.87</td>
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</tr>
<tr>
<td>2</td>
<td>77.80</td>
<td>2.75</td>
</tr>
<tr>
<td><strong>Refractory Thickness (m)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.25</td>
<td>75.59</td>
<td>2.75</td>
</tr>
<tr>
<td>0.3</td>
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<td>0.4</td>
<td>42.44</td>
<td>2.75</td>
</tr>
<tr>
<td><strong>Emissivity</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.5</td>
<td>63.44</td>
<td>2.75</td>
</tr>
<tr>
<td>0.8</td>
<td>60.87</td>
<td>2.75</td>
</tr>
<tr>
<td>0.95</td>
<td>59.58</td>
<td>2.75</td>
</tr>
</tbody>
</table>

It is seen that the boundary conditions given initially are probably incorrect due to the large discrepancy in the two calculated thermal coefficients. The effect of changing each boundary condition is considered in turn. It can be seen that the outer kiln temperature has the greatest effect on the thermal convection coefficient ($h$). It was proposed that this variable was incorrect.
Assuming the convection coefficient (h) calculated from the empirical equation (7.2) is correct, h can be substituted into equation (7.3) to calculate the outer temperature of a newly relined kiln.

\[
\frac{k(T_1 - T_3)}{R_2} \ln \frac{R_2}{R_1} = 1.32 \left( \frac{T_3 - T_\infty}{2R_3} \right)^{1/4} R_3 \frac{1}{(T_3 - T_\infty)} + R_3 \sigma \varepsilon (T_3^4 - T_\infty^4) \quad (7.4)
\]

Using the above equation, the outer temperature was found to be 265°C. The outer kiln temperature was then later found using thermocouples placed on three newly relined kiln shells in operation. The temperature was found to be on average 200°C. This confirmed that the data initially given was incorrect, and suggested the outer kiln temperature on newly relined kilns was between 200°C and 265°C. The empirical equation (7.2) was also taken to be a reasonably reliable means of calculating the convection coefficient (h).

### 7.2 Wear Properties of Refractory

The thickness of the refractory after the kiln has been in use at the stage of overheating is unknown. The only tabulated conditions during the overheating stage are the inner and outer temperatures of the kiln.

With the temperature conditions known, equation (7.4) can be used to calculate the inner radius of the kiln at the stage of overheating. The initial inner radius of the kiln is known. From practical experience, the duration for the kiln outer temperature to reach overheating is on average 40 weeks. This enables wear rates to be calculated for different kiln outer temperatures by dividing the change of refractory thickness by the time duration for the wear to occur. These are described in table (7.2) below.
Table 7.2 Wear Rate and final inner radii calculated for different boundary conditions

Subsequent inspection of an overheated kiln refractory lining revealed a final inner radius of between 1.8m and 1.9m along the length of the kiln, confirming that the final outer temperature was in the region of 400°C. It also suggests that the convection coefficient calculated from equation (7.2) was correct.

7.3 Theoretical Stresses due to Thermal Changes

Only a few years after the publication in 1829 of Poisson's famous memoirs on the theory of elasticity, Duhamel (1838) investigated modifications to allow for temperature change. Today, almost all references give thermo-elastic equations, Timoshenko and Goodier (1970) being among the more prevalent.

Thermo-elastic equations incorporate thermal expansion, where normal strains occur unaccompanied by normal stresses. Therefore solutions of thermal stress require superposition of strains, attributed to temperature, onto existing normal strains. In cylindrical co-ordinates the resulting equations are:

\[
\varepsilon_t = \frac{1}{E} \left( \sigma_t - \nu (\sigma_0 + \sigma_z) \right) + \alpha T \quad (7.5a)
\]
7. Thermal Loading Effects

\[ \varepsilon_\theta = \frac{1}{E} \left( \sigma_\theta \cdot v(\sigma_r + \sigma_z) \right) + \alpha T \]  
\[ (7.5b) \]

\[ \varepsilon_z = \frac{1}{E} \left( \sigma_z \cdot v(\sigma_r + \sigma_\theta) \right) + \alpha T \]  
\[ (7.5c) \]

When temperature distribution is symmetrical with respect to the cylinder centre, the displacements are a function of radius only. This enables stresses and strains to be described as a function of radius and radial displacement. The governing equations are:

\[ \varepsilon_r = \frac{\partial U}{\partial r} \]  
\[ (7.6a) \]

\[ \varepsilon_\theta = \frac{U}{r} \]  
\[ (7.6b) \]

\[ \frac{\partial \sigma_r}{\partial r} + \frac{\sigma_r - \sigma_\theta}{r} = 0 \]  
\[ (7.6c) \]

These can be used for any cylindrical geometry and boundary conditions. The hollow cylinder with radial temperature variation is of particular interest and solutions for radial displacement and stresses can be found a number of ways.

Timoshenko and Goodier (1970) find a solution for radial displacement of a hollow cylinder with restricted ends (longitudinal strain is zero) to be:

\[ U = \frac{(1 + v) \alpha}{(1 - v) r} \int_a^r \left[ T_r \, dr + C_1 \, r + \frac{C_2}{r} \right] \]  
\[ (7.7) \]

For a cylinder with unrestrained ends, a uniform axial stress should be superimposed. This stress is calculated from:
7. Thermal Loading Effects

\[ \sigma_t = \frac{-2E \alpha}{(b^2 - a^2)} \int Tr \, dr \]  
\[ (7.8) \]

a = inner radius  
b = outer radius

Saint Venant's Principle [Timoshenko and Goodier 1970] restricts the application of this equation to areas away from the areas of application of the superimposed stresses (i.e. away from the ends).

Using a second method of complex variables, stresses can be found in a slightly different form. This need not be dealt with due to the above being sufficient for this investigation.

For a composite cylinder, the boundary conditions would include an interface stress and displacement. Four equations of the form (7.7) would need to be simultaneously solved. This would incorporate four unknown constants which would prove extremely difficult to solve. Both these approaches can be simplified using shell theory. Shell theory assumes the temperature gradient through the shell thickness is linear. This approach causes greater mathematical simplification when considering composite cylinders, and proves most effective and useful. For a free-edged multi-shell cylinder subjected to a temperature gradient, both axial and hoop stresses are present, with only circumferential strain \( (\varepsilon_\theta) \) occurring [Timoshenko 1959]. The axial and hoop stresses at points remote from the ends reduce to:

\[ \sigma_\theta = \sigma_\theta = \sigma = \frac{E}{1 - \nu} (\varepsilon_\theta - \alpha \Delta T) \]  
\[ (7.9) \]

For the assumption that Poisson's ratio is equal for all the materials, the following expression is obtained for \( \varepsilon_\theta \):

\[ \varepsilon_\theta = \frac{A_a E_a \alpha_a \Delta T_a + A_b E_b \alpha_b \Delta T_b}{A_a E_a + A_b E_b} \]  
\[ (7.10) \]
\[ \alpha = \text{coefficient of thermal expansion} \]
\[ A = \text{area} \]
\[ \text{subscript } a = \text{material } a \]
\[ \text{subscript } b = \text{material } b \]

\[ \Delta T = \text{Average of the temperature differentials at the boundaries of the materials (i.e.} \]
\[ \Delta T_a = \frac{1}{2}(\Delta T_1 - \Delta T_2), \quad T_1 = \text{outer temperature of material } a, \quad T_2 = \text{inner temperature of material } a). \]

A comparison of the effects due to different loading types is pertinent to the investigation. The stresses and strains due to thermal changes in this chapter can be compared with those due to self weight loading in the previous chapter.

The first model analysed is a plane strain cross section of the kiln. All boundary conditions are known except the interface temperature between the steel and refractory. This can be calculated using the conduction equation (7.1a). The heat flux through the refractory must equal the heat flux through the steel. This leaves the interface temperature as the only unknown. The equation used is:

\[
\ln \left( \frac{R_3}{R_2} \right) \left( T_1 - T_2 \right) = \ln \left( \frac{R_2}{R_1} \right) \left( T_2 - T_3 \right) \quad \frac{2 \pi k_s l}{2 \pi k_c l} \]

\[ s = \text{subscript for steel} \]
\[ c = \text{subscript for concrete} \]
\[ T_1 = \text{Inner temperature} \]
\[ T_2 = \text{mid-face temperature} \]
\[ T_3 = \text{outer temperature} \]
Now that all the boundary conditions have been established, the stress due to a temperature change on the inside and outside can be calculated using equations (7.9) and (7.10).

\[ \epsilon_{\theta} = \frac{t_s E_s \alpha_s 1/2(\Delta T_1 + \Delta T_2) + t_c E_c \alpha_c 1/2(\Delta T_2 + \Delta T_3)}{t_s E_s + t_c E_c} \]  

(7.12)

\( \epsilon_{\theta} \) from equation (7.12) can be inserted into equations (7.13) for the stresses as follows:

At inner:
\[ \sigma_{\text{steel}} = \frac{E_s}{1 - \nu_s} (\epsilon_{\theta} - \alpha_s \Delta T_1) \]

At mid-face:
\[ \sigma_{\text{steel}} = \frac{E_s}{1 - \nu_s} (\epsilon_{\theta} - \alpha_s \Delta T_2) \]  

(7.13)

At mid-face:
\[ \sigma_{\text{conc}} = \frac{E_c}{1 - \nu_c} (\epsilon_{\theta} - \alpha_c \Delta T_2) \]

At outer:
\[ \sigma_{\text{conc}} = \frac{E_c}{1 - \nu_c} (\epsilon_{\theta} - \alpha_c \Delta T_3) \]

Different boundary conditions were studied to simulate conditions imposed on the kiln. The results can be found in table (7.3) and compared to the FEM results. The use of the above equations enable an easy cross check of the more accurate FEM results.

7.4 Finite Element Modelling of Stresses due to Thermal Effects

A selection of FEM element type had to be made for the thermal modelling. The elements considered were axisymmetric continuum and axisymmetric shell elements. Axisymmetric continuum elements were more appropriate. The stresses and strains
7. Thermal Loading Effects

Through the kiln thickness were of major interest, and axisymmetric continuum elements would generally produce more accurate results than the shell elements in this respect. Axisymmetric elements also enabled interface elements to be incorporated into the model if required.

The first finite element model simulated the theoretical thermal behaviour. This was modelled using twelve one-dimensional axisymmetric elements through the kiln thickness. This had many more gauss points through the thickness than was necessary. The boundary conditions are the same used in chapter (7.1) with the steel conductivity being 52 W/mK. The temperature at the interface was found to be within 0.2°C of the theoretical interface temperature. The thermal gradient obtained from the 1-D FEM was found to be close to linear and is shown in figure (7.1).

The second and third models used two-dimensional axisymmetric continuum elements to find the stresses induced by thermal change through the kiln. The models simulated the heating up of the kiln from ambient temperature. Different final thermal conditions were investigated. Results can be seen in table (7.3).
At this stage, it was possible to compare the stresses due to thermal change (table (7.3)) and self weight loadings (table (6.1)). It can be seen that the thermal loading has far greater effect on the stresses and strains than the self weight loading. Even if extreme cases were considered, the thermal loading effect on stress was in the order of 10 times larger than the self weight loading effect. The thermal effect can then be assumed to be the failure loading mechanism, and the self weight loading can be considered insignificant to initial failure. Development of further intricate thermally loaded models can therefore commence.

The following models incorporated the riding ring support into a two-dimensional axisymmetric model. The riding ring was obviously the greatest stress area because of the discontinuity. This was confirmed by failure occurring at the riding ring weldment.

Mesh refinement was done to check the convergence of the results. The model consisted of four elements through the steel shell thickness and fifteen through the refractory. The number of elements was biased towards the riding ring discontinuity. Only the riding ring and 2m on either side were modeled with the ends being modeled as symmetric. The stresses away from the riding ring were not relevant. No interface elements were incorporated because the exact interface characteristics between the steel and refractory were unknown. The spikes welded onto the inside of the shell to hold the refractory to the shell, as described in chapter (2), enabled the interface to be assumed solid. A section of the model showing the discontinuity can be seen in appendix D.

The constant variables for the kiln problem are as follows:

- Steel thickness: 32mm
- Concrete thermal expansion: 0.73 at 1000°C
- Steel thermal expansion: 10.8E-6 /°C
- Steel Young’s Modulus: 207GPa

A number of different cases were investigated and are listed below.

Case 1) The kiln is heated from ambient temperature (25°C) to an inner temperature of 1150°C and outer temperature shown in table (7.3). The kiln is assumed to have recently been relined with a refractory thickness of 0.3m.
Case 2) The kiln is heated from ambient temperature to an outer temperature of 100°C and inner temperature shown in table (7.3). The kiln is assumed to have recently been relined with a refractory thickness of 0.3m.

Case 3) The kiln is heated from ambient temperature to an outer temperature of 100°C and inner temperature of 1150°C. The thickness of the refractory is varied according to table (7.3).

Case 4) The kiln is heated from ambient temperature to an outer temperature of 100°C and inner temperature of 1150°C. The kiln is assumed to have recently been relined with a refractory thickness of 0.3m. The Young's Modulus of the concrete is varied according to table (7.3).

Case 5) The refractory thickness changes from 0.3m to 0.22m. The change of thickness changes the temperatures through the kiln and thereby the stresses. This case models the thermal effect due to refractory thinning down from the time of relining to over-heating.

Case 6) Water is sprayed on the outside of the kiln shell lowering the temperature from 400°C by the amount shown in table (7.3). The refractory thickness is 0.22m. This is assumed to be the thickness when the outer temperature of the kiln is overheating at 400°C.

The effect of different conditions imposed on the kiln can be seen, and the results from calculation and FEM can be compared in table (7.3) below. The amount of variation of each variable is chosen by the accuracy of the information gathered on the kilns in chapter (2).
<table>
<thead>
<tr>
<th>Case</th>
<th>Outer temp Change</th>
<th>Inner temp Change</th>
<th>Thickness (m)</th>
<th>EConcrete (Pa)</th>
<th>Calculated stresses</th>
<th>ABAQUS Stresses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>75</td>
<td>1125</td>
<td>0.3</td>
<td>5.3E+10</td>
<td>-3.79E+08</td>
<td>2.15E+08</td>
</tr>
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<td></td>
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<td>125</td>
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<td>5.3E+10</td>
<td>-2.47E+08</td>
<td>1.77E+08</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>1125</td>
<td>0.3</td>
<td>5.3E+10</td>
<td>-4.01E+08</td>
<td>2.21E+08</td>
</tr>
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<td>2</td>
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<td>75</td>
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<td>-3.79E+08</td>
<td>2.15E+08</td>
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<tr>
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<td>1125</td>
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<td>-4.11E+08</td>
<td>1.83E+08</td>
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<td>5.3E+10</td>
<td>-9.52E+07</td>
<td>1.79E+07</td>
</tr>
</tbody>
</table>

Table 7.3 Calculated and ABAQUS stresses for different boundary conditions
From table (7.3), the calculated and ABAQUS results were seen to correlate within 20%.

The effect of heating the kiln from ambient temperature was seen to produce stresses well above the yield stress of the steel. This can be partially attributed to the originally given equilibrium outer kiln temperature being 100°C. It can be seen from case 1) that the greater the outer temperature change, the less the thermal stresses induced. The effect of the kiln heating over a period of three days enables shrinkage and creep to compensate to a large degree if high stresses were induced. This would cause stress relieving during heating of the kilns after relining.

Changing the equilibrium inner temperature in case 2) has a relatively small effect on the stresses compared to changing the outer kiln temperature. What must be remembered however, is fluxing can occur at high temperatures causing refractory wear, therefore high temperatures should be avoided.

Changing the thickness of the refractory in case 3), was seen to have only a relatively small effect on the stresses compared to changing the outer kiln temperature. This confirmed that relining the kilns with a thicker layer of refractory would not be detrimental to the kilns.

The effect of the refractory's Young's modulus showed a significant effect on the stresses (case 4)). The originally assumed modulus of 25GPa produced stresses in the order of what was expected. The modulus found later by laboratory experimentation of 53GPa doubles the stresses. It should be noted here that the laboratory modulus was found at ambient temperatures. It was shown in chapter (2.1.2.c) that the modulus of unfired refractories can decrease by half due to temperature rise of 300°C. Therefore the Young's modulus decreases by half during operation and the stresses found using a modulus of 25GPa are the true stresses.

The effect of the refractory thinning (case 5), showed stresses of relative insignificant effect. Furthermore, because of the time elapsing and the high temperatures involved during this thinning process, the stresses would be relieved by a creep process described in chapter (2.3.1).

The effect of water being sprayed on the kiln (case 6), showed a considerable effect on the stresses. These stresses in the steel are induced instantaneously by water suddenly being turned on. There is no time for creep or stress dissipation to occur. This effect is
therefore critical and will cause failure in both the steel and refractory. This high stress coupled with the corrosive water environment confirms the mode of failure as stress corrosion cracking established by material examination in chapter (5).

The failure of the refractory will cause the refractory to thin resulting in further thermal stresses. The refractory is mostly in compression and able to sustain higher stresses than if in tension with the cold compressive strength being 85MPa. The stresses due to water spraying are larger than 85MPa even using a refractory Young’s Modulus of 25MPa. Water spraying is therefore considered detrimental to the refractory. There are however other unquantifiable effects such as softening of the refractory which will relieve stresses in the refractory to a certain extent.

Correlation between the calculated and ABAQUS results above enabled further modelling cases to be done aimed at specific problems. The major problem was that of the steel shell cracking at the inlet riding ring. Further finite element models were constructed incorporating the riding ring. The welds were not modeled but were assumed to cause further concentration of stresses. This further modelling enabled additional boundary condition changes to be modelled as described in cases 7) and 8).

Case 7) Water spraying on both sides of the kiln riding ring. The maximum steel stresses are calculated.

Case 8) Water spraying on one side of the kiln riding ring only. The maximum steel stresses are calculated.

Once again stresses were found for varying boundary conditions. The results of the riding ring models can be seen in table (7.4) below showing the maximum stresses in the steel shell.
7. Thermal Loading Effects

<table>
<thead>
<tr>
<th>Case</th>
<th>Outer temp Change</th>
<th>Inner temp Change</th>
<th>Thickness concrete (m)</th>
<th>Ecombe (Pa)</th>
<th>Max hoop Stress (Pa)</th>
<th>Max axial Stress (Pa)</th>
</tr>
</thead>
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<tr>
<td>1</td>
<td>75</td>
<td>1125</td>
<td>0.3</td>
<td>5.3E+10</td>
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<td>5.3E+10</td>
<td>6.30E+08</td>
<td>7.15E+08</td>
</tr>
</tbody>
</table>

Table 7.4 ABAQUS Steel Stresses for Different Boundary Conditions

It can be seen that the riding ring discontinuity increased the stresses due to thermal loading. Water spraying on one side of the riding ring produced resultant stresses twice as large as those produced by water being sprayed on both sides. This showed the significance of avoiding water being sprayed on the kilns, especially on one side of the riding ring only.

A number of difficulties arising in the above finite element analyses caused the procedure to alter and warrant mention. These will be described below.

The first difficulty encountered was the attempt to isolate stresses due to a temperature change after thermal equilibrium had been reached. ABAQUS could not calculate the initial thermal conditions without producing the relevant stresses in reaching those conditions. Three solutions to this were found. The first was to subtract the stresses before and after the temperature change under observation. The second was to write a user file to designate each node with an initial thermal equilibrium temperature. The third was to remove and then replace all the elements after the equilibrium state had been reached. If elements are removed, their stress and strain values are reset to zero, but their nodal temperatures remain. The third solution, even though being slightly
unconventional, was chosen as being the simplest and easiest to use. This method was checked and confirmed using single one dimensional and axisymmetrical elements before being implemented.

A second difficulty arose with the attempt to use coupled temperature-displacement analysis with composite shell elements. This approach was attempted in order to simulate the non-symmetrical cases. These were refractory breaking away from the steel shell, and the inclusion of an air inlet pipe. The use of such a scheme would prove easy and efficient, where material could be removed at any instant, simulating refractory breaking away from the shell. The air inlet pipe investigation could also be easily incorporated into the shell by a material removal and insertion of new boundary conditions at the pipe inlet. An investigation into the addition of gussets could be done by adding connecting beams from the kiln shell to a stiffening beam (the riding ring). These investigations could not be undertaken because the ABAQUS code was found to be faulty in this particular context. The code was unable to run shell coupled temperature analyses with a composite structure. This was checked by simple test models which produced incorrect results. This was verified by another, prominent, ABAQUS user, Dr C. Mercer. The analysis could have been replaced by three dimensional elements, but this was avoided for the reasons explained earlier in this chapter. Extrapolation of the former results was considered adequate, even though undesirable. Further non-axisymmetric models or redesigns could not be investigated. The procedure, however, was clarified and could be undertaken under different circumstances.
8. Holographic Non-destructive Testing Quantified by Finite Element Modelling

A method of establishing the correct material properties and parameters for the kiln case study is needed. Furthermore, a method for determining the extent of flaws observed in the kiln would also be desirable. The size and conditions of the kilns limit the techniques available for such an investigation. However, holographic interferometry is one technique which has been used for similar investigations, leading to qualification of flaws and stresses in a wide variety of practical objects such as tyres, castings and pressure vessels. The problem arises when the quantification of the flaws and parameters is required.

The theory of holographic interferometry can be found in appendix (E.2). This chapter firstly describes the components used to investigate holographic quantification. Secondly, it describes the finite element modelling of the components used, and finally, results of the quantification are given.

8.1 Components used for Holographic Qualification

The comparative holographic and finite element analyses were performed on an aluminium alloy cylindrical shell with dimensions as in figure (8.1).

![Figure 8.1 Dimensions of Cylinders used for Holographic Interferometry Quantification](image-url)
The first analysis was done on the unflawed reference cylinder shown in figure (8.1). Similar cylinders incorporating manufactured grooves and cracks were then analysed. The flaws investigated were two axisymmetric grooves (one outer and one inner), and two thumbnail cracks as shown in appendix (E.3).

The cylindrical shells were deformed by applying an internal pressure using a dead weight hydraulic tester. Different pressures and crack depths were analysed. The resultant out of plane displacements were then compared using the holographic and finite element techniques.

Further analyses were conducted to investigate the effect of changing the axisymmetrical groove depth on radial displacement. The radial displacement was calculated theoretically, by shell finite elements and by axisymmetric finite elements. The analytic calculations can be found in appendix (E.4).

The modelling of the above described cylindrical shells will now be discussed.

**8.2 Finite Element Modelling of Flawed Cylinders**

The ABAQUS finite element package was used for modelling the cylinders. Three types of elements were available for the analyses of the cylinders. Axisymmetric elements could be used for the reference and axisymmetrically cracked cylinders. 3-D elements could be used for all geometries but were avoided due to the complexity of the mesh generation and also in order to minimize computer time. Shell elements combined with line spring elements were proposed as the best modelling solution, which will be described later in more detail.

The initial analyses of the reference and two axisymmetrically flawed cylinders were performed using axisymmetric elements. Similar analyses using Shell-Line spring elements were used to validate the latter model. The thumbnail cracked cylinders could then be analysed with a better degree of confidence.

The basic concept of shells and line spring elements at cracks was first proposed by Rice (1972) and further investigated by Parks and White (1982). Line spring elements introduce a local solution into a shell model of the uncracked geometry. This is accomplished by allowing additional freedom in the shell model along the line of the crack, embedding the local solution into the global response.
The line spring is a series of 1-D elements placed along the flaw, with the flaw depth being denoted at each node. The local flexibility is calculated from existing solutions for single edge notch specimens in plane strain. Approximations are incorporated due to the use of 2-D solutions embedded into the shell model.

The force and moment versus the relative displacement and rotation relationships provide the constitutive model, and are derived from local solutions to single edge cracked plane strain specimens. These relationships can be found in appendix (E.5). Elastic and fully plastic solutions are used to construct an approximate elastic plastic model.

The line spring elements use quadratic interpolation of displacement and rotation components along the crack, so they are compatible with second order shell elements which are used to form the shell.

8.3 Mesh Generation and Refinement of FEM

The axisymmetric model incorporated 8 node elements with a minimum of two elements (six gauss points) through the thickness of the cylinder. This is described as adequate for thin walled cylinders [Zienkiewicz and Chaung 1967]. Mesh refinement was done within reasonable distance from the crack. A sensitivity study was done to verify the refinement.

The shell model incorporated 8 node elements positioned at the mid thickness of the cylinder wall. The variable thickness shown in figure (8.1) above, had to be described using a number of node sets of different thickness and different radial positions. Again, refinement was arranged around the cracks.

The ease of changing the crack geometry using line spring elements proved invaluable. The inner axisymmetrical groove could be changed to an outer configuration with a single sign change, and the shell mesh did not need to be altered for the different thumbnail cracks: the line spring elements were merely repositioned or designated new flaw depths.
8.4 Post Processing of FEM

The use of axisymmetrical elements enabled calculation of radial displacements along the cylinder length. These could then be converted to out of plane displacement on the cylinder surface using a spreadsheet. However, the ABAQUS post processor was able to plot out of plane contour displacements for the shell-line spring elements on the cylinder surface, thus eliminating the spreadsheet process.

To simulate the interference fringes, the post processor had to calculate out of plane contour lines in the positions of the fringes. From the ABAQUS output deck, a maximum and minimum out of plane displacement could be found. The minimum out of plane displacement was clearly zero at the edges of the cylinder. The maximum out of plane displacement value can be found in the ABAQUS output file. From this and the theory in appendix (E.2), the number of contours that the processor has to use to simulate the correct number of holographic fringes can be established. The out of plane displacement between each holographic fringe is equal, therefore the post processor was needed to calculate equally spaced out of plane displacement contours.

The processor could then be set up to have a minimum out of plane displacement of zero, a maximum out of plane displacement of the maximum fringe displacement, and a number of levels equal to the number of fringes. This simulated the dark fringes of the holograms exactly.

8.5 Results of Holographic Quantification

Results were found from the axisymmetric elements and the shell-line spring elements. The axisymmetrically modelled reference cylinder and the two axisymmetrically grooved cylinders produced similar displacement contours to the Shell-Line Spring element contours. This instilled confidence in the latter which were then used for the final results.

The post processor was able to display the shell elements in a similar format to the holograms. The holograms and corresponding finite element simulations of the reference cylinder and flawed cylinders are shown in appendix (E.6). It is clearly shown that the grooves and cracks cause a superposition on the reference displacement. The extremely close correlation between the holograms and the finite element simulation indicated that simulation using the above procedure was not only possible,
but was also extremely accurate. Different flaw shapes produced different contour patterns, and different flaw depths produced different numbers of contours. Radial displacements of flawed and unflawed components were therefore quantifiable. This enables in situ components to be analysed without damaging or removing the component.

Further investigation was done on the axisymmetrically grooved cylinder. The groove depth was varied from zero depth to 95% through thickness. The effect on radial displacement of changing the groove depth is shown in figure (8.2).

![Figure 8.2 Effect of groove depth on radial displacement](image)

The above supports the quantification of all flaw depths, showing that a critical flaw depth can be related to a particular radial displacement. Any greater radial displacement than the critical radial displacement would cause failure. The gradients in the above figure (8.2) are not affected by a change of length, change of thickness, nor a change of groove angle. Results supporting this are shown in appendix (E.7).
The parameters of a finite element model can be manipulated to construct an output which correlates with the component's *in situ* holographic output. Once correlation has been achieved, so has quantification of the material properties and the flaw shapes and sizes. The kiln case study can be similarly investigated enabling the quantification of material properties and flaws. This observation technique can also serve as confirmation of the ABAQUS investigation into the detailed areas of the kiln case study.

Another approach possible, is to model the component using critical values of the parameters. If the holographic output indicates a more severe case than the critical finite element model, the component is in danger of failing and should be relieved of present loadings.

With the quantification of material properties and flaws possible, the predominant failure modes can be assessed. However, the quantification of the kiln properties and flaws was not undertaken because Highveld Steels considered the completed level of investigation sufficient and wished to avoid further costs. The quantification method could be used at a later date if need be.
9. Assessment of Failure Modes

A number of failure modes have been discussed in previous chapters. It has been ascertained that, because the temperature of the kiln steel shell was kept below 40 percent of the steel melting point, the kiln failure mode was not creep. It was, however, found that the initial fracture can be attributed to stress corrosion cracking. This failure mechanism was initiated by high thermally induced stresses, coupled with water being sprayed on the kiln shell. In section 2.5.4 it was shown that stress corrosion cracking was unquantifiable without extensive experimentation, therefore the life assessment due to this failure mode is not possible. Preventative measures can, however, be undertaken by avoiding spraying water on the kilns. This will remove the high thermal stress and the corrosion mechanism.

Fatigue stresses in the kiln case study are the stresses due to the self-weight loading. The stresses are cyclic and change from compression to tension as the kiln rotates. The presence of the large static thermal stress considerably decreases the fatigue limit as shown in section 2.3.3d therefore fatigue is possible. Fatigue failure would not usually occur with cyclic fatigue stresses as low as those found in the kilns. With the present flaw sizes, fatigue will occur irrespective of the low fatigue stresses. A fatigue life assessment due to the cyclic self-weight loading will therefore be investigated, giving the safe-life of the kilns in the absence of stress corrosion cracking.

The uncertainty of the kiln material properties and the lack of experimental data do not allow for an accurate life assessment to be done. However, it is possible to make assumptions and reasonable guesses in order to establish a suspected life expectancy. This will also enable the effect on life expectancies of different redesigns to be compared (provided the same properties are used).

9.1 Fatigue Fracture Life Assessment

Many engineering structures are subjected to cyclic loads during service. The estimation of fatigue life before fracture failure is therefore an essential part of engineering design.

The kiln case study is assumed to have initial flaws or cracks at the inlet riding ring. The fatigue stresses at the flaws are known from the investigation in chapter (6) on self-weight loading. The initial flaw sizes and shapes can be quantified by applying the
procedure developed in chapter (8) as well as from observations of the kiln. These observations have indicated that the cracks are through-thickness cracks. The fatigue fracture case of through-thickness cracks was covered in chapter (2.5.3) and will now be elaborated upon.

For simplicity, the stress amplitude ($\Delta \sigma$), stress ratio ($R$), frequency ($f$), temperature effects on materials ($T$) etc. are assumed constant. The kinetics of fatigue crack growth shall be assumed to be described by the one single equation (3.10) over the entire range of interest. The fracture toughness of the material is given by $K_c$.

From the above information, the following can be determined:

$$\sigma_{\text{max}} = \Delta \sigma (1 - R) = \text{constant}$$

$$\sigma_{\text{min}} = R \sigma_{\text{max}} = R \Delta \sigma / (1 - R)$$

$$\Delta K = Y\Delta \sigma \sqrt{a \pi} \quad \text{from equation (3.9)}$$

$$\therefore a_f = \frac{K_c^2}{\pi \sigma_{\text{max}}^2}$$

$$\frac{da}{dN} = A (\Delta K)^{2n} = \pi^n A (\Delta \sigma)^{2n} a^n \quad \text{from equation (3.10)}$$

Integrating equation (3.10), gives the following equation for fatigue life.

$$N_f = \frac{1}{\pi^n A (n - 1) (\Delta \sigma)^{2n} a_i^{a(n - 1)} Y^{2n}} \left[ 1 - \left( \frac{a_i}{a_f} \right)^{(n - 1)} \right]$$

(9.1)

$N_f$ = number of cycles to failure

$a_i$ = initial crack length

$a_f$ = final crack length

$A, n$ = constants
In order to find the number of cycles to failure of the kiln from the above equation, the constants and parameters need to be known. Ideally, these need to be found from experimentation using the actual steel of the kilns at the appropriate temperatures. This was not however possible, therefore alternatives had to be found. Some of the constants for the steel are commonly documented; where others have been evaluated during previous investigations into the case study.

For carbon steels with 0.2% proof stress of less than 600 N/mm², the constants A and n have been established from the mechanical analysis of some 350 results of tests on defective welds [Garwood 1979]. The values at 100°C are:

\[
A = 0.95 \times 10^{-11} \\
n = 1.5
\]

These values are temperature dependent therefore experimental data should be gathered at different temperatures for an accurate assessment.

The stresses due to self-weight become negative and then positive as the kiln rotates through 360 degrees, therefore the stress range is twice the maximum stress found in chapter (6).

\[
\therefore \Delta \sigma = 52\text{MPa}
\]

The geometric correction factor is equal to 1 because the flaw is assumed a through crack in an infinite plate. Care must be taken when the final flaw size is large because the problem becomes a finite plate. The stresses for such a problem could then be determined by finite element methods.

The largest flaw size observed in the kilns without causing catastrophic failure thus far is 2m. It can be seen from the fatigue life equation that final flaw size is relatively insignificant to the fatigue life with the initial flaw size having a far greater effect. The initial flaw size can be found by the holographic nondestructive technique described in an earlier chapter, and the final flaw size can be found using fracture toughness principles already discussed. These were not undertaken due to cost and time constraints. The largest flaw size present in the kilns at present is estimated by the kiln operators as 0.2m which will be used as a reference. The final flaw size is not suggested, however, a number of scenarios are given in table (9.1).
It can be clearly seen that the initial flaw size is of great importance to the life prediction of the kiln, therefore, the quantification of the initial flaw size must be accurate. The flaws in the kilns at present vary from very small to 0.3m. The life prediction of each kiln can be made from inspection of the present flaws. The final flaw size is seen to have little effect on the fatigue life. The stress range has a marked effect, however, if the value found in chapter (6) has been established using accurate properties, a high degree of confidence eliminates any significant variation.

The time to failure of the kiln for a flaw size greater than 10cm is regarded as extremely short. Preventative methods are therefore pertinent to the survival of the kilns.

Repair of the flaws by welding may arrest the fatigue fracture providing the high thermal stresses and corrosion mechanism are not reintroduced. The effect of welding causes further stress concentration at the heat effected zone. Cracking will merely re-begin in this area if similar stresses are applied. The introduction of gussets will have a similar effect, where stress concentrations at the gusset base will occur, again causing...
failure. The above life prediction approach is not valid if the high thermal stresses or the corrosion mechanism are allowed to prevail.

The repair of the kilns is best done without causing stress concentrations of any kind. One way of achieving this is by welding a metal cylinder to the inside of the kiln shell under the cracked regions. This is only possible after the removal of the refractory. The longer the added cylinder, the further the stress concentration will be from the cracked region. This will cause no additional thermal stresses and will not over-stiffen the cracked area avoiding further stress concentration.
10. Conclusions

A design procedure for high temperature engineering components has been developed. The procedure followed the path of a case study investigation, namely pre-reduction kilns.

Comprehensive data was collected on the case study. This included the kiln parameters, boundary conditions, major problems encountered and past redesign ventures. It was noted that the consequences of the past redesign ventures were not evaluated.

A literature survey was done in order to gain insight into the problem. Relevant literature on the kiln problem covering design procedures, material properties, failure modes and non-destructive testing was surveyed. There was limited literature found on design procedures covering corrective redesigning, however similar approaches to the normal design procedures could be adopted. Literature on the material properties of the kiln and their behaviour during \textit{in situ} conditions included the refractory castable and steel shell. Limited information was found on refractory castables. New refractory castables are continually being produced with differing properties, therefore the documentation on the material refractories was limited. However, the steel properties before the kiln was submitted to operational conditions were well documented.

An overall design procedure for the investigation into the kiln and similar \textit{in situ} high temperature problems was successfully achieved. This differed from normal design procedures in that the original design already existed. The redesign procedure focuses more on analysis of \textit{in situ} component conditions and material properties and a means of comparing redesigns. A redesign process for the kiln problem was established providing a framework of actions and a management control function for solving the problem. The process began with the preparation for the problem which was simply collecting data. Objectives were then clearly set out with the use of an objective tree. Limits and boundaries were established using a performance specification method. This suited the kiln problem enabling two levels of generality to be investigated. These were a low level for changing the design features to solve the problem, and a high level for establishing testing techniques. The level at which detail was investigated was achieved by considering essential functions. This successfully described and separated functions of the design procedure and enabled methods for accomplishing each function to be chosen. Convergence on the solution of redesigning was achieved by simple deduction from the sub-solutions of the functions.
During the literature survey it was found that not all pertinent material properties were documented. Further material property evaluation was done on the kiln Hicast KL refractory castable. The thermal expansion coefficient was found to be as documented (0.7% at 1000°C) and linear over the temperature range of 50°C to 1000°C. The investigation was undertaken because, if non-linearity occurred, the resultant thermal stresses would differ greatly. The refractory cold crushing strength was found to be 85MPa which is considerably higher than conventional refractory. The refractory Young’s Modulus was found to be 53GPa at room temperature which was higher than expected. This was attributed to laboratory tests being done at room temperature rather than operational temperatures. The thermal expansion of the refractory during heating up of the kilns was found to be countered by the shrinkage of the refractory while drying, causing stress relieving. The refractory was also found to creep at the operating kiln temperatures causing further stress relief. This explained why the kilns do not rupture during the heating up process after new refractory castable had been laid.

The present in situ steel condition was also evaluated. It was found that the steel properties in most areas of the kiln were found to possess the original qualities and properties according to specification. However, in areas of high stress and temperature, the material properties had deteriorated. Metallurgical tests showed there to have been overheating in the kiln flame tip area producing inferior material properties. In the areas where blasting out of refractory had been experimented with, fast fracture cracking had been found. This clearly indicated failure due to the blasting out of refractory by "Rapid Refractory Removal". At the high stress area of the riding ring, stress corrosion cracking was observed. This area was also being sprayed with cooling water, supporting the suggested failure theory.

The effect of the above inferior material properties increases the kiln susceptibility to failure. Investigations done using the original material properties were therefore not conservative. The magnitude of the stresses found from investigations, even though inaccurate in magnitude, could still be relatively compared. Different boundary conditions were implemented and the effect of the most severe cases of loading conditions were compared. This comparative stress analysis could still commence and be useful in the design by allowing influential loading to be ignored. A sensitivity study was able to determine the relative effect of changing material parameters. This enabled efficient and effective deductions to be made on re-designs and alterations.
There were two loading cases investigated, namely self weight and thermal loading. The effect of self weight on the kiln was the first loading case evaluated. The positioning of the support riding rings along the kiln were found to be correct. Modelling began with a simple steel cantilever cylindrical shell and ended with a shell model of the entire kiln with riding ring supports. The maximum steel stress due to self weight in the final model was found to be well below the steel yield stress and therefore self weight is unlikely to be the cause of initial failure.

The following investigation was into the effect due to thermal changes. The thermal boundary conditions were firstly investigated. This showed a discrepancy in the thermal convection and the thermal conduction of the kiln. To assess where the discrepancy lay, a sensitivity analysis was done on influencing parameters. The outer temperature of the kiln was found to be the parameter causing the most effective change. It was proposed that the outer temperature of the kiln during operation was initially given incorrectly. This was subsequently confirmed by a practical investigation.

The refractory wear rate was investigated next. Different boundary conditions were shown to produce wear rates in the region of 3mm and 6mm per week. The final inner radius after wear ranged from 1.8m to 1.9m. The temperature through the kiln was verified using theoretical and FEM techniques. From this, the interface temperature between the steel and refractory could be found. With the boundary conditions found above, different scenarios of temperature changes were used to investigate the stresses induced. The results show thermal stresses were in the order of 10 times the stresses due to self weight loading. This enabled the self weight loading to be considered insignificant to the initiation of failure. Further models were then investigated. These concentrated on specific problem areas of the kiln. The riding ring area at the inlet end of the kiln was homed in on because of the presence of observed flaws. Water being sprayed on the kiln outside caused the highest stresses of 380MPa. This is well above the yield stress. Water spraying on one side of the riding ring increased this stress even further. The effect of refractory falling out and the addition of gussets were not able to be investigated. The finite element package incorporated an error. The only option to overcome this was to consider much more intricate model types.

A non-destructive testing technique was developed for analysing in situ structures as large as the kilns. This enabled material properties and flaws to be qualified and quantified. The investigation showed the non-destructive technique of holographic interferometry was the best means of qualifying in situ component conditions and
flaws, however, quantification was also necessary. The finite element technique was used to quantify holographic interferometry. Manufactured flawed cylinders were used as vehicles for this quantification. Holographic fringe patterns were simulated by the finite element method. The two were found to have similar out of plane displacement contour shapes and number of contours. This enabled material properties and a flaw shape and depth to be associated with a contour shape and number of contours. Therefore quantification was possible.

The failure modes were then assessed. The investigation was directed at determining and countering significant failure modes rather than quantifying them. Quantification was found to be almost impossible with the lack of accurate and extensive experimental data. The mode causing the initial failure of the kilns was found to be stress corrosion cracking. This failure mechanism could be prevented by the relieving of high thermal stresses and corrosion mechanism (i.e. the avoiding of water spraying on the kilns). However, the cracking had already occurred with cracks still remaining, introducing fatigue fracture. A life assessment due to fatigue fracture of the kiln was done. With the lack of experimental material and flaw data, the results were considered inaccurate. However, the method could be used as a means of comparing the original design with redesigns.

Using data from other literature sources an estimated life assessment was done. This found that kilns incorporating cracks larger than 10cm are expected to be operational for less than 3 years, provided high thermal stresses and corrosion are eradicated from the problem. This life period could be extended by repair, providing the repair did not cause extreme stress concentrations.

The procedure verified that an initial overall view of the component was important to finding the problem areas. Problems could then be isolated and investigated individually. Different loading types could be individually investigated enabling the exclusion of the insignificant loadings. With the affecting loading types and the corresponding failure mode, the problems were found to be easily solvable. The progressive modelling approach allowed the effect of adding new conditions to the kiln to be quantified. Specific problem areas could then be homed in on. Quantification of flaw size and shape enabled in situ components to be investigated and incorporated into the procedure and were pertinent to fatigue life assessment.
11. Recommendations

The following recommendations are made for furthering the thesis investigation:

1) Investigate other cases similar to the kiln problem. This will enable different avenues of the procedure (such as different failure modes and loading conditions) to be studied in greater depth.

2) Further holographic quantification be done of different flaw geometries using different component shapes. This will improve the method for quantifying in situ component conditions and flaws.

The following recommendations are made for the kiln case study:

i) The effect of design alterations must be thoroughly investigated before implementing them. This can be achieved by using the procedure developed in this thesis and comparing redesigns with the original design.

ii) The inside temperature of the kiln is to be kept below the slagging temperature of the refractory (1200°C) thereby avoiding refractory decay and subsequently decreasing the wear rate.

iii) The welding done on the kiln is to be of an acceptably high quality. This will avoid stress concentrations thereby reducing susceptibility to crack initiation.

iv) Water cooling of the kilns should be avoided. Water cooling produces extreme stresses and stress change rates which will initiate cracking. The high stresses and thermal shock coupled with the corrosive water environment is extremely detrimental to the kilns. If water cooling is unavoidable, spray on both sides of the riding ring rather than one side only.

v) The refractory is not to be removed from the kiln by blasting. This has proved fatal in the past.

vi) Gussets and other discontinuities which will cause stress concentrations should be minimised. The effects of any changes made must be carefully studied.
11. Recommendations

vii) The Thickness of the refractory lining ought to be increased (by about 30%) to increase production time between relining of the kilns. The addition of refractory to the kilns will have minimum effect on the self weight loading which itself is not the cause of crack initiation or critical stresses. An increase in the lining thickness will also reduce the thermal stresses and avoid overheating.

viii) The investigation of different refractory types to improve the wear rate should continue. This has proved to be an effective means of decreasing the relining frequency and protecting the steel shell.

ix) Experimental data that will enable accurate life assessments to be done on the present design and redesigns needs to be obtained. The present life expectancy of the kilns can be ascertained enabling an inspection timetable to be developed. This will also enable accurate comparison of the initial design and redesigns.
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Appendix A

This appendix shows photographs of the pre-reduction kiln under study.

Figure A1 shows the side view of the kiln riding ring section. The relative size of the kiln can be compared to the waist high railing on the walkway. The sprinklers can be clearly seen. They spray water on the top of the kiln which flows down the sides as the kiln rotates. The air inlets shown are complicated by the kiln having to rotate. The spikes protruding from the kiln shell are the remains of the blasting technique used for extracting refractory. The gussets added to the riding ring are also clearly visible. Figure A2 shows the kiln from a different viewpoint. The support bearing, the blast spikes and gussets are clearly visible. Figure A3 shows the degradation of the film deposit on the kiln shell. The streaky nature the erosion suggests water plays a major role in this effect. Power cables to the air fans are also visible.

Figure A1 Side view of inlet riding ring section of kiln.
Figure A2 Bottom front view of kiln showing riding ring and supports

Figure A3 Close up view of the kiln shell
Appendix B

Appendix B shows all the material properties available for the steel and refractory which construct the kiln.

B.1. Steel Properties

| BS number: | BS 1501-151 (grade 430) |
| Steel type: | Killed or fully killed carbon steel |
| High temperature properties |

Chemical Analysis:

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<th>%</th>
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</tr>
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<tr>
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<tr>
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<tr>
<td>Nickel</td>
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Nitrogen Content < 0.012%
Deoxidation: Aluminium may be used in addition to Silicon

Material Properties

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<th>Value</th>
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<td>Modulus of rigidity:</td>
<td>79.3 GPa</td>
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<tr>
<td>Poisson’s Ratio:</td>
<td>0.29</td>
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<tr>
<td>Yield Strength:</td>
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<tr>
<td>Yield Stress (or 0.2% proof stress):</td>
<td>202 MPa</td>
</tr>
</tbody>
</table>
Appendix B

Stress Rupture Value: 57 MPa
(rupture time = 10000 hr at 500°C)

Charpy V-notch not specified

B.2. Refractory Properties

Refactory name: Hicast KL
Manufacturer: Vereeniging Refractories
Description: Alumino-Silicate high strength castable

Chemical Analysis:

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<th>Percentage</th>
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</thead>
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<tr>
<td>Cr₂O₃</td>
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<tr>
<td>Na₂O + K₂O</td>
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</tr>
</tbody>
</table>

Physical Properties

Maximum service Temperature: 1650°C
Maximum particle size: 6.0 mm
Bulk density: 2660 kg/m³
Thermal conductivity at 1000°C: 1.6 W/mK
Thermal expansion at 1000°C: 0.73%
Cold crushing strength Dried at 110°C: 85 MPa
Fired to 500°C: 94 MPa
Fired to 1000°C: 102 MPa
Appendix C

Appendix C shows the stress contour plots for self weight loading of the kiln.

Figure C1 (Case 1) Mises stress contour plot of cantilever steel shell, rigidly supported on right hand side.
Stresses shown for outside of steel

Figure C2 Mises stress contour plot of entire kiln (steel shell, refractory lining, charge and riding ring). Support is modeled as rollers on riding ring.
Stresses shown for outside of steel
Figure C3 Mises stress contour plot of entire kiln (steel shell, refractory lining, charge and riding ring). Support is modeled as rollers on riding ring.
Stresses shown for inside of refractory
Appendix D

Appendix D shows stress contour plots for thermal loading of the pre-reduction kiln.

**Figure D1** (Case 7) Mises stress contour plot of axisymmetric cross section of kiln at riding ring. Water sprayed on both sides of riding ring.

**Figure D2** (Case 7) Axial stress contour plot of axisymmetric cross section of kiln at riding ring. Water sprayed on both sides of riding ring.
Figure D3 (Case 7) Hoop stress contour plot of axisymmetric cross section of kiln at riding ring. Water sprayed on both sides of riding ring.

Figure D4 (Case 8) Mises stress contour plot of axisymmetric cross section of kiln at riding ring. Water sprayed on one side of riding ring.
Figure D5 (Case 8) Axial stress contour plot of axisymmetric cross section of kiln at riding ring. Water sprayed on one side of riding ring.

Figure D6 (Case 8) Hoop stress contour plot of axisymmetric cross section of kiln at riding ring. Water sprayed on one side of riding ring.
Appendix E

Appendix E firstly shows the apparatus used for taking holographic pictures. Secondly, the theory of holographic interferometry is described. Thirdly, the components used for the quantification are described. Fourthly, an expression for the theoretical radial displacement of the axisymmetrically grooved cylinder is found. Fifthly, the results of the holographic quantification are shown, and lastly, the effect of changing the parameters on the radial displacement are tabulated.

E.1 Photograph of Holographic Apparatus

Figure E.1 shows the apparatus used for making holographic interferograms. The camera is movable and can be directed at any angle. Interferograms can be developed and viewed on site using this equipment.
**E.2 Theory of Holographic Interferometry**

Holographic interferometry allows the highly accurate measurement of surface displacement. It determines the full displacement field on a surface of a body under the influence of a disturbing load. The recording of holograms is done by the arrangement shown in figure (E.2).

![Holographic Interferometry Arrangement](image)

**Figure E.2 Holographic Interferometry Arrangement**

This shows coherent light being emitted from a laser and the light being split by a beam splitter. One section of the light illuminates the object under inspection before reaching the photographic plate, and the other serves as a reference beam going straight to the photographic plate.

The described arrangement detects the component of motion towards the holographic plate (assuming a small angle between the viewing and illumination direction). This
motion causes fringes (black contour bands) to form on the image of the object as a result of interference between light scattered from the object on the plate, and light from the reference beam. This causes constructive (light fringes) and destructive (dark fringes) interference to occur. The fringe pattern displays a contour map of out of plane displacement. The difference in out of plane displacement between each fringe is half a wavelength of laser light (about $3 \times 10^{-4}\text{mm}$).

There are numerous methods of interpreting holographic interferograms. A summary of these is given by Briers (1976). The most commonly used, and most accurate, is the zero order fringe method. It is based on the change in optical path from the source to the observer which is related to the fringe order. Provided the illumination and viewing directions are in the direction of displacement, the following equation can be used to calculate the out of plane displacement:

$$d = \frac{m \lambda}{2}$$  \hspace{1cm} (E.1)

$d =$ displacement  
$m =$ number of fringes away from zero fringe  
$\lambda =$ wave length of laser light (633 nm for ruby laser)

In many cases it is known that a particular point on the hologram does not alter in out of plane displacement. If a displacement is known at one fringe (normally zero displacement), the out of plane displacements at the other fringes can be calculated using the above equation. Therefore the displacements can be found on any surface of any shape.

The sensitivity of the above technique enables extremely small discontinuities on a surface to be observed. Therefore such changes such as delaminations and cracks are detectable even if out of view.

The qualities of the holographic non-destructive testing technique allow it to be used as an accurate qualitative tool for analysing in situ components. In particular, it is able to detect flaws in components with a great deal of reliability. In order to use this technique to its full potential, quantification of holographic interferometry would be vital. This would not only give knowledge of the existence of a flaw, but also determine the size of the flaw. With this knowledge, the designer may deem the
observed flaw as safe or critical. In industry, components are often large and immovable. This holographic technique could be used for quantifying flaws in structures as large as the kiln case study without damaging or moving the component.

It is essential therefore that more effort be made not only to extend the promise of holographic methods for flaw detection but also to quantify the flaws detected. There is a need to be able to study the mechanics of flawed parts which have a response to the holographic method. In this way the path towards quantification can begin. The flawed parts used for the quantification will now be described.

**E.3 Components used for Holographic Quantification**

The flawed cylinders used as vehicles for the holographic quantification are shown below with dimensions.

![Diagram of Axisymmetric Inner and Outer Grooved Cylinder](image)

**Figure E.3** Axisymmetric Inner and Outer Grooved Cylinder
E.4 Theoretical Radial Displacement of Cylinders with Axisymmetric Grooves

The theoretical estimation of the radial displacement of a cylinder under pressure was kept as simple as possible. The groove and force geometry are shown in figure (E.6).
The cylinder was assumed to be "thin" in relation to the radius, and can be modelled as in figure (E.7). It is assumed that elastic conditions prevail.

\[
\frac{w_0}{2\beta^2D} = \frac{M_0}{2\beta^3D} + \frac{Q_0}{2\beta^3D} + w_m
\]
Appendix E

\[
\frac{\partial w_0}{\partial x} = -\frac{M_0}{\beta D} - \frac{Q_0}{2\beta^2 D}
\]  

(E.2)

\(w_0\) = total radial deflection  
\(w_m\) = membrane deflection  
\(\beta^4 = \frac{3(1-v^2)}{r^2 t^2}\)

\[D = \frac{E t^3}{12 (1-v^2)}\]

Inserting the following boundary condition:

\[\frac{dw}{dx} = 0 \text{ at } x = 0\]

and solving for \(M_0\) and \(Q_0\) gives:

\[M_0 = \frac{P r d}{2\beta} \]  

(E.3)

\[Q_0 = -2 M_0 \beta\]

\(P\) = inner pressure  
\(d\) = depth of flaw  
\(r\) = radius of cylinder

Therefore the radial deflection can be found from the depth of the groove and the thickness of the cylinder as follows:
Appendix E

\[
\frac{w_0}{w_m} = 1 + \frac{d}{t} \left[ \frac{3}{4(1 - \nu^2)} \right]^{1/2}
\]

With Poisson's ratio = 0.3

\[
\frac{w_0}{w_m} = 1 + 0.91 \frac{d}{t} \quad (E.4)
\]

The second term of equation (E.4) shows the effect due to the groove. The first is the reference or membrane deflection.

**E.5 Description of ABAQUS Line-Spring Element**

Line-spring element are an addition to shell elements to describe a flaw. They are inserted into the shell mesh at the position of the flaw. At each point along the flaw, a local orthonormal basis system is defined, \( t \) being tangent to the shell along the flaw, \( n \) being normal to the shell and \( q \) being the cross product of the above. The flaw can be defined on the inner or outer surface of the shell since the shell normal \( (n) \) defines the surface direction.

The relative motion between points on either side of the flaw is defined by the following five generalized strains [Hibbitt, Karlsson and Sorensen 1989].

**Mode I**
- Opening displacement: \( \Delta U_1 = (U_B - U_A) \cdot q \)
- Opening rotation: \( \Delta \phi_1 = (\phi_B - \phi_A) \cdot t \)

**Mode II**
- Through thickness shear: \( \Delta U_{II} = (U_B - U_A) \cdot n \) (E.5)

**Mode III**
- Anti plane shear: \( \Delta U_{III} = (U_B - U_A) \cdot t \)
- Anti plane shear: \( \Delta \phi_{III} = (\phi_B - \phi_A) \cdot q \)
Appendix E

\[ U = \text{displacement} \]
\[ \phi = \text{angular rotation} \]
\[ A, B = \text{positions on either side of crack} \]

E.6 Results of Holographic Quantification

The post processor was able to display the shell elements in a similar format to the interferograms. The interferograms and corresponding simulation of the reference cylinder, axisymmetrically grooved cylinder, and thumbnail cracked cylinders are shown below.
Figure E.8 Reference Cylinder Interferogram and Simulation
Internal Pressure change = 200psi
Figure E.9 Inner and outer Grooved Cylinder

Internal Pressure = 200psi
Depth of grooves = thickness/2
a) Interferogram

b) ABAQUS simulation

Figure E.10 Simulation of axial thumb nail crack

Internal pressure change = 200psi

Crack depth = 2/3 thickness
Figure E.11 Simulation of axial thumb nail crack
Internal pressure change $= 100$psi
Crack depth $= 2/3$ thickness
Figure E.12 Simulation of circumferential thumb nail crack
Internal pressure = 100psi
Crack depth = 2/3 thickness
Figure E.13 Simulation of circumferential thumb nail crack
Internal pressure = 200psi
Crack depth = 2/3 thickness
E.7 Effect of changing parameters on radial displacement

The following table shows the effect of changing different parameters in the holographic quantification analysis. The radial deflection of the inner and outer grooved cylinder was investigated while certain parameters were changed. This enabled the effect of each parameter to be established. It can be seen that none of the listed parameters besides the groove depth greatly affects the radial deflection. The groove angle does change as the thickness parameter is changed, but because the groove angle has no effect on the deflection, it has no effect when the thickness parameter is changed.

<table>
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<th>Groove Depth / thickness</th>
<th>Cylinder Length (mm)</th>
<th>Thickness (mm)</th>
<th>Groove Angle (deg)</th>
<th>Outer groove Max defl. mm</th>
<th>Max outer defl.</th>
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<td>Groove Depth</td>
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Figure E.14 The effect of different parameters on radial deflection of a grooved cylinder