COPYRIGHT AND CITATION CONSIDERATIONS FOR THIS THESIS/ DISSERTATION

○ Attribution — You must give appropriate credit, provide a link to the license, and indicate if changes were made. You may do so in any reasonable manner, but not in any way that suggests the licensor endorses you or your use.

○ NonCommercial — You may not use the material for commercial purposes.

○ ShareAlike — If you remix, transform, or build upon the material, you must distribute your contributions under the same license as the original.

How to cite this thesis
EXPERIMENTAL AND NUMERICAL STRUCTURAL PERFORMANCE ASSESSMENT OF A DIRECT FIRED ROTARY KILN

by

Damian Dariusz Tyczynski

200918595

Submitted in fulfilment of the requirements for the degree MAGISTER INGENIERIAE in MECHANICAL ENGINEERING Faculty of Engineering and the Built Environment at the UNIVERSITY OF JOHANNESBURG

SUPERVISOR: Dr. D.M. Madyira

CO-SUPERVISOR: Dr. W. Cieslakiewicz

April 2018
ABSTRACT

Rotary kilns are advanced thermal processing systems which are used to process solid material at elevated temperatures. Rotary kilns operate by holding the processed material at a specific temperature for a specific amount of time. There are two main types of rotary kilns i.e. directly fired and indirectly fired rotary kilns. In directly fired rotary kilns, the process material is in direct contact with the combustion flame and flue gases. On the other hand, for the indirect fired kiln, the process material is in an inert environment, which prevents direct contact with the combustion flame and flue gases.

Due to the elevated operating temperatures, complex loading scenarios arise. These may lead to mechanical deformations such as axial distortion, transverse distortion, blistering, necking, banana distortion, misalignment and kinks. These behaviours complicate structural performance assessments of rotary kilns. Furthermore, due to the equipment’s size and harsh working environment, it makes it difficult to conduct structural performance tests to obtain experimental data. Therefore, numerical modelling tools may be applied to optimise the design of the rotary kilns.

The main purpose of this work was to develop a numerical model for the structural performance of a direct-fired rotary kiln pilot plant, developed by Drytech International Pty. Ltd, and to validate the model by using experimental data. The main study focused on the stress and strain state of the kiln for three load cases namely (1) when the empty kiln is rotating (2) when the kiln is rotating and loaded without heat and (3) when the kiln is rotating and loaded with heat.

Through real time strain measurements, transient response validation data was obtained. The experimentally gathered strain measurements were transformed, and the principal stress and strain state was calculated for each point in time. A validated transient finite element numerical model was then develop using Abaqus CAE.

Percentage fill and temperature was varied using the numerical model to determine the influence that these parameters had on the direct-fired rotary kiln pilot plant. The investigation confirmed that the structural behaviour of the direct-fired rotary kiln pilot plant is influenced by fill percentage and temperature i.e. the strain and stress variation is dependent on the response of the kilns structure to different load applications.

To further develop the study on direct-fired rotary kilns, full scale experimental data should be gathered from full-scale industrial kilns and validated by the use of a numerical modelling tool such as Abaqus CAE.
ACKNOWLEDGEMENTS

I would like to personally thank the following people for their help, support and patience in helping to make this dissertation a success:

- A special thank you goes to Dr. D. M. Madyira and Dr. W. Cieslakiewicz for their time, guidance and the willingness to share their knowledge and wisdom with me. Without their guidance this work would not have been possible.
- To my family D. S. Tyczynski, M. S. Tyczynski, A. J. Tyczynski and Z. B. Krawczyk, for all their love and support and for giving me the opportunity to further develop my knowledge in this field of study that I love, the funding and always a kind and caring word of advice and encouragement. Without them my dream of one day becoming an engineer would have never been possible.
- To Drytech International Pty. Ltd. for allowing me to utilise their facilities and for their kindness.
- To Mr. R. Carpenter, managing director at Drytech International Pty. Ltd., for the time off from work, the company’s facilities, constantly giving his opinion and access to Drytech’s database
- Mr. W. Grimm, for his assistance and knowledge about platinum concentrate
- Mr. D. Scholtz for his involvement in the experimental data gathering
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>DECLARATION</td>
<td>i</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>ii</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>ix</td>
</tr>
<tr>
<td>NOMENCLATURE</td>
<td>x</td>
</tr>
<tr>
<td>LIST OF APPENDICES</td>
<td>xi</td>
</tr>
<tr>
<td>CHAPTER 1.0: INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Problem Statement</td>
<td>3</td>
</tr>
<tr>
<td>1.2.1 Motivation</td>
<td>3</td>
</tr>
<tr>
<td>1.2.2 Aims</td>
<td>3</td>
</tr>
<tr>
<td>1.2.3 Objectives</td>
<td>3</td>
</tr>
<tr>
<td>1.3 Scope of Work</td>
<td>4</td>
</tr>
<tr>
<td>1.4 Research Methodology</td>
<td>4</td>
</tr>
<tr>
<td>1.5 Concluding remarks</td>
<td>5</td>
</tr>
<tr>
<td>CHAPTER 2.0: LITERATURE REVIEW</td>
<td>6</td>
</tr>
<tr>
<td>2.1 General Remarks</td>
<td>6</td>
</tr>
<tr>
<td>2.2 Background into the Development of Kilns</td>
<td>6</td>
</tr>
<tr>
<td>2.3 Directly Fired Rotary Kilns</td>
<td>7</td>
</tr>
<tr>
<td>2.3.1 Introduction to Directly Fired Kilns</td>
<td>7</td>
</tr>
<tr>
<td>2.3.2 Different Forms of Rotary Kilns</td>
<td>8</td>
</tr>
<tr>
<td>2.3.3 Design and Application</td>
<td>8</td>
</tr>
<tr>
<td>2.4 Performance of Directly Fired Rotary Kilns</td>
<td>15</td>
</tr>
<tr>
<td>2.4.1 Heat Transfer Mechanisms</td>
<td>15</td>
</tr>
<tr>
<td>2.4.2 Heat Transfer Mechanisms Applied to Directly Fired Rotary Kilns</td>
<td>16</td>
</tr>
<tr>
<td>2.5 Structural Numerical Analysis of Directly Fired Kilns</td>
<td>18</td>
</tr>
<tr>
<td>2.5.1 Introduction to Finite Element Analysis</td>
<td>18</td>
</tr>
<tr>
<td>2.5.2 Basic Approach of Finite Element Analysis</td>
<td>19</td>
</tr>
<tr>
<td>2.5.3 Non-linear Finite Element Analysis</td>
<td>21</td>
</tr>
<tr>
<td>2.5.4 Johnson-Cook Model</td>
<td>22</td>
</tr>
<tr>
<td>2.5.5 Finite Element Analysis Approach to Directly Fired Rotary Kilns</td>
<td>26</td>
</tr>
<tr>
<td>2.6 Concluding Remarks</td>
<td>28</td>
</tr>
</tbody>
</table>
CHAPTER 3.0: EXPERIMENTAL PROCEDURE

3.1 General Remarks

3.2 Experimental Aims

3.3 Material Description

3.4 Apparatus

3.4.1 Overview of the Direct Heated Rotary Kiln Developed by Drytech

3.4.2 SG-Link Equipment

3.4.3 Strain Gauge Rosette

3.4.4 Temperature Data Logger

3.4.5 K-Type Thermocouple

3.5 Experimental Procedure and Set-up

3.6 Experimental Matrix

3.6.1 Independent Variables

3.6.2 Dependent Variables

3.6.3 Constant Variables

3.6.4 Experimental Matrix

3.7 Concluding Remarks

CHAPTER 4.0: EXPERIMENTAL RESULTS

4.1 General Remarks

4.2 Relevant Stress Theory

4.2.1 Strain Transformation

4.2.2 Principal Strains

4.2.3 Principal Stresses

4.3 Results

4.3.1 Node Orientation on the Direct Fired Rotary Kiln Shell

4.3.2 Principal Stress Calculations

4.3.3 Strain Measurement Due to Rotation

4.3.4 Strain Measurement Due to Rotation and Loading

4.3.5 Strain Measurement Due to Rotation, Loading and Heating

4.3.6 Results Due to Rotation

4.3.7 Results Due to Rotation and Loading

4.3.8 Results Due to Rotation, Loading and Heating

4.4 Concluding Remarks

CHAPTER 5.0: NUMERICAL ANALYSIS OF A DIRECT FIRED ROTARY KILN

5.1 General Remarks

5.2 The Finite Element Analysis
5.2.1 Geometry ...................................................................................................................... 65
  5.2.1.1 Direct-Fired Rotary Kiln Shell ........................................................................................ 65
  5.2.1.2 Refractory Lining ........................................................................................................... 66
  5.2.1.3 Rider Ring ...................................................................................................................... 67
  5.2.1.4 Drive Sprocket............................................................................................................... 67
5.3 Material Properties ............................................................................................................... 68
5.4 Numerical Model Constraints ............................................................................................... 69
  5.4.1 Boundary Conditions..................................................................................................... 69
  5.4.2 Loading Conditions ........................................................................................................ 71
5.5 Mesh ..................................................................................................................................... 72
  5.5.1 Mesh Sensitivity ............................................................................................................ 72
  5.5.2 Mesh Sensitivity Results ................................................................................................ 73
  5.5.3 Discussion of Mesh Sensitivity Results.......................................................................... 74
5.6 Thermal Stress Analysis......................................................................................................... 76
  5.6.1 Abaqus Thermal Stress Model ...................................................................................... 77
  5.6.1.2 Transient Heat transfer ................................................................................................. 77
  5.6.1.3 Kiln Structural Response Analyses ................................................................................ 79
  5.6.1.4 Numerical Model Discussion ......................................................................................... 80
  5.6.2 Parameter Influence on the Numerical Model ............................................................. 82
  5.6.2.2 Parameter Change Results ............................................................................................ 83
5.7 Chapter Summary ................................................................................................................. 86

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS ................................................................. 87
  6.1 Background Remarks ........................................................................................................ 87
  6.2 Conclusion .......................................................................................................................... 87
  6.3 Recommendations ............................................................................................................. 88

REFERENCES .................................................................................................................................. 89

A.0 APPENDICES ............................................................................................................................ 95
  A.01. Mechanical Drawings of the Rotary Kiln by Drytech International Pty. Ltd. .................. 96
  A.02. Report on Drying Platinum Concentrate by Mr. W. Grimm ........................................... 97
  A.03. Basic Hand Calculations – Bending Moment ................................................................. 100
  A.04. Basic Hand Calculations – Principal Stress ....................................................................... 101
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Common Mechanical Deformations of Rotary Kilns: a) Ovality, b) Necking, c) Axial Distortion, d) Blistering, e) Banana Distortion</td>
<td>2</td>
</tr>
<tr>
<td>2.1</td>
<td>Direct Heating Counter Flow Rotary Kiln</td>
<td>8</td>
</tr>
<tr>
<td>2.2</td>
<td>Typical Mechanical Components of a Directly Fired Counter Current Rotary Kiln</td>
<td>9</td>
</tr>
<tr>
<td>2.3</td>
<td>Typical Thrust Roller Arrangement</td>
<td>9</td>
</tr>
<tr>
<td>2.4</td>
<td>Single Leaf Seal Arrangement</td>
<td>11</td>
</tr>
<tr>
<td>2.5</td>
<td>Double Leaf Seal Arrangement</td>
<td>11</td>
</tr>
<tr>
<td>2.6</td>
<td>Labyrinth Seal Arrangement</td>
<td>12</td>
</tr>
<tr>
<td>2.7</td>
<td>a) Cast-able Refractory Lining, b) Brick Refractory Lining</td>
<td>13</td>
</tr>
<tr>
<td>2.8</td>
<td>Heat Transfer Modes within Direct Heated Kilns</td>
<td>17</td>
</tr>
<tr>
<td>2.9</td>
<td>Discretisation of a Domain into Elements and Nodes</td>
<td>19</td>
</tr>
<tr>
<td>3.1</td>
<td>Sprocket and Chain Arrangement on Drytech's Direct Fired Rotary Kiln Pilot Plant</td>
<td>31</td>
</tr>
<tr>
<td>3.2</td>
<td>Support Configuration of the Direct Fired Rotary Kiln at Drytech</td>
<td>32</td>
</tr>
<tr>
<td>3.3</td>
<td>Fan and Burner Arrangement of the Direct Fired Rotary Kiln</td>
<td>32</td>
</tr>
<tr>
<td>3.4</td>
<td>Burner Arrangement</td>
<td>33</td>
</tr>
<tr>
<td>3.5</td>
<td>SG-Link®-LXRS Wireless Nodes</td>
<td>34</td>
</tr>
<tr>
<td>3.6</td>
<td>Wiring of a SG-Link®-LXRS Wireless Node for Quarter Bridge Configuration</td>
<td>34</td>
</tr>
<tr>
<td>3.7</td>
<td>The WSDA®-Base-101 Analog Output Base Station</td>
<td>35</td>
</tr>
<tr>
<td>3.8</td>
<td>Typical Strain Gauge</td>
<td>35</td>
</tr>
<tr>
<td>3.9</td>
<td>HUATO S220-T8 Temperature Data Logger</td>
<td>37</td>
</tr>
<tr>
<td>3.10</td>
<td>Orientation of Inner K-Type Thermocouples</td>
<td>39</td>
</tr>
<tr>
<td>3.11</td>
<td>Arrangement of Inner and Outer Thermocouples on the Direct Fired Rotary Kiln</td>
<td>39</td>
</tr>
<tr>
<td>3.12</td>
<td>Prepared Area for Bonding</td>
<td>40</td>
</tr>
<tr>
<td>3.13</td>
<td>Orientation of Strain Gauges</td>
<td>41</td>
</tr>
<tr>
<td>3.14</td>
<td>Secured Lead Wires from the Rosette Strain Gauge with Epoxy Resin</td>
<td>41</td>
</tr>
<tr>
<td>3.15</td>
<td>Final Set-up of the Rosette Strain Gauge and Node Configuration</td>
<td>42</td>
</tr>
<tr>
<td>3.16</td>
<td>Complete Configuration to acquire the Experimental Data</td>
<td>42</td>
</tr>
<tr>
<td>3.17</td>
<td>Digital Scale</td>
<td>43</td>
</tr>
<tr>
<td>3.18</td>
<td>Loaded Platinum Concentrate</td>
<td>43</td>
</tr>
<tr>
<td>3.19</td>
<td>Final Assembly of the Directly Fired Rotary Kiln</td>
<td>44</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1</td>
<td>Schematic of Node Orientation</td>
<td>50</td>
</tr>
<tr>
<td>4.2</td>
<td>Orientation of the Principal Plane</td>
<td>52</td>
</tr>
<tr>
<td>4.3</td>
<td>Reference Point for Horizontal Alignment of Nodes</td>
<td>53</td>
</tr>
<tr>
<td>4.4</td>
<td>Measured Strain vs Time due to Rotation of the Unloaded Kiln</td>
<td>53</td>
</tr>
<tr>
<td>4.5</td>
<td>Principal Stress vs Time due to Rotation of the Unloaded Kiln</td>
<td>54</td>
</tr>
<tr>
<td>4.6</td>
<td>Principal Stress vs Time for One Complete Rotation of the Unloaded Kiln</td>
<td>54</td>
</tr>
<tr>
<td>4.7</td>
<td>Measured Strain vs Time due to Rotation and Loading</td>
<td>55</td>
</tr>
<tr>
<td>4.8</td>
<td>Principal Stress vs Time due to Rotation and Loading</td>
<td>55</td>
</tr>
<tr>
<td>4.9</td>
<td>Principal Stress vs Time for One Complete Rotation when the Kiln is Loaded</td>
<td>56</td>
</tr>
<tr>
<td>4.10</td>
<td>Thermocouple Placement for the Direct Fired Rotary Kiln</td>
<td>56</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 2.1: Degrees of Freedom for Different Analysis Approaches [29] ..................................................... 20
Table 3.1: Chemical Composition of Kiln Shell Material S 355 JR in Percentage [50] ................................. 29
Table 3.2: Mechanical Properties of the Kiln Shell Material S 355 JR at t≤16l [50] [51] .............................. 30
Table 3.3: Chemical Composition of EN 8 in percentage [52] [53] ............................................................. 30
Table 3.4: Material Properties of EN8 [54] [55] [56] .................................................................................... 30
Table 3.5: Refractory Technical Specifications [57] [58] [59] .................................................................. 30
Table 3.6: Thermal Properties of Platinum Concentrate [60] [61] ............................................................. 30
Table 3.7: Strain Gauge Configuration [69] ............................................................................................... 36
Table 3.8: Technical Specifications of UFRA-1-350 [70] ........................................................................ 36
Table 3.9: Specifications of the S220 Thermocouple Thermometer [71] ................................................... 37
Table 3.10: Preliminary Experimental Matrix ............................................................................................ 46

Table 4.1: Experimental Results due to Rotation ....................................................................................... 60
Table 4.2: Experimental Results Due to Rotation and Loading ............................................................... 61
Table 4.3: Experimental Results Due to Rotation, Loading and Heating ................................................ 62
Table 4.4: Experimental Validation Data .................................................................................................. 62

Table 5.1: Material Properties as Assigned to the Individual Components in the Numerical Model ...... 69
Table 5.2: Boundary Conditions for the Numerical Model of the Pilot Plant Kiln ..................................... 70
Table 5.3: Mesh Sensitivity Simulation Results ......................................................................................... 73
Table 5.4: Average Stress along the Kiln Outer Shell for the Numerical Model ...................................... 80
Table 5.5: Fill Percentage Variation ......................................................................................................... 82
Table 5.6: Temperature Variation ............................................................................................................. 82
## NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\varepsilon^p$</td>
<td>Accumulated Plastic Strain</td>
<td></td>
</tr>
<tr>
<td>$\theta$</td>
<td>Angle of the Strain Gauge Placement</td>
<td>$^0$</td>
</tr>
<tr>
<td>$A$</td>
<td>Area</td>
<td>$m^2$</td>
</tr>
<tr>
<td>$T$</td>
<td>Current Temperature</td>
<td>$^\circ$C</td>
</tr>
<tr>
<td>$r$</td>
<td>Damage Built up Plastic Strain</td>
<td></td>
</tr>
<tr>
<td>$D$</td>
<td>Damage Variable</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon^*$</td>
<td>Dimensionless Strain Rate</td>
<td></td>
</tr>
<tr>
<td>$T^*$</td>
<td>Dimensionless Temperature</td>
<td></td>
</tr>
<tr>
<td>$\sigma_{eq}$</td>
<td>Equivalent Flow Stress</td>
<td>$MPa$</td>
</tr>
<tr>
<td>$\varepsilon_\theta$</td>
<td>Experimental Strain</td>
<td>$\mu$mm/mm</td>
</tr>
<tr>
<td>$T_f$</td>
<td>Fluid Temperature</td>
<td>$^\circ$C</td>
</tr>
<tr>
<td>$q_x$</td>
<td>Heat Conduction</td>
<td>$W$</td>
</tr>
<tr>
<td>$Q$</td>
<td>Heat Convection</td>
<td>$W$</td>
</tr>
<tr>
<td>$E_b$</td>
<td>Heat Radiation</td>
<td>$W$</td>
</tr>
<tr>
<td>$h$</td>
<td>Heat Transfer Coefficient</td>
<td>$W/m^2^\circ$C</td>
</tr>
<tr>
<td>$D_i$</td>
<td>Inner Diameter of the Kiln</td>
<td>$m$</td>
</tr>
<tr>
<td>$A$</td>
<td>Initial Yields Stress at Room Temperature</td>
<td>$MPa$</td>
</tr>
<tr>
<td>$D_1$ to $D_5$</td>
<td>Material Constraints for J-C Failure Model</td>
<td></td>
</tr>
<tr>
<td>$\varepsilon_1$</td>
<td>Maximum Principal Strain</td>
<td>$\mu$mm/mm</td>
</tr>
<tr>
<td>$\sigma_1$</td>
<td>Maximum Principle Stress</td>
<td>$MPa$</td>
</tr>
<tr>
<td>$\sigma_m$</td>
<td>Mean Stress</td>
<td>$MPa$</td>
</tr>
<tr>
<td>$T_{melt}$</td>
<td>Melting Temperature</td>
<td>$^\circ$C</td>
</tr>
<tr>
<td>$\varepsilon_2$</td>
<td>Minimum Principal Strain</td>
<td>$\mu$mm/mm</td>
</tr>
<tr>
<td>$\sigma_2$</td>
<td>Minimum Principal Stress</td>
<td>$MPa$</td>
</tr>
<tr>
<td>$\theta_p$</td>
<td>Orientation of the Maximum Principal strain</td>
<td>$^0$</td>
</tr>
<tr>
<td>$\theta_q$</td>
<td>Orientation of the Minimum Principal strain</td>
<td>$^0$</td>
</tr>
<tr>
<td>$O_D$</td>
<td>Outside Diameter of the Kiln</td>
<td>$m$</td>
</tr>
<tr>
<td>$O_v$</td>
<td>Ovalization</td>
<td>$m$</td>
</tr>
<tr>
<td>$\gamma_{xy}$</td>
<td>Plane Shear Strain (x-y plane)</td>
<td>$\mu$mm/mm</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Poisson's Ratio</td>
<td></td>
</tr>
<tr>
<td>$\Delta H$</td>
<td>Radial Displacement</td>
<td>$mm$</td>
</tr>
<tr>
<td>$T_{room}$</td>
<td>Room Temperature</td>
<td>$^\circ$C</td>
</tr>
<tr>
<td>$G$</td>
<td>Shear Modulus</td>
<td>$GPa$</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Stefan-Boltzmann Constant</td>
<td>$W/m^2^\circ$C</td>
</tr>
<tr>
<td>$B$</td>
<td>Strain Hardening Effect</td>
<td></td>
</tr>
<tr>
<td>$n$</td>
<td>Strain Hardening Effect</td>
<td></td>
</tr>
<tr>
<td>$C$</td>
<td>Strain Rate</td>
<td></td>
</tr>
<tr>
<td>$\sigma^*$</td>
<td>Stress Triaxiality Ratio</td>
<td></td>
</tr>
<tr>
<td>$T_w$</td>
<td>Surface Temperature</td>
<td>$^\circ$C</td>
</tr>
<tr>
<td>$\partial T/\partial x$</td>
<td>Temperature Gradient</td>
<td>$N/A$</td>
</tr>
<tr>
<td>$T_{bb}$</td>
<td>Temperature of Blackbody</td>
<td>$K$</td>
</tr>
<tr>
<td>$k$</td>
<td>Thermal Conductivity</td>
<td>$W/m^2^\circ$C</td>
</tr>
<tr>
<td>$\varepsilon_x$</td>
<td>Transformed strain (x-direction)</td>
<td>$\mu$mm/mm</td>
</tr>
<tr>
<td>$\varepsilon_y$</td>
<td>Transformed strain (y-direction)</td>
<td>$\mu$mm/mm</td>
</tr>
<tr>
<td>$E$</td>
<td>Young's Modulus</td>
<td>$GPa$</td>
</tr>
</tbody>
</table>
LIST OF APPENDICES

A.0. Appendices ......................................................................................................................................................... 95
A.01. Mechanical Drawings of the Rotary Kiln by Drytech International Pty. Ltd. ............................ 96
A.02. Report on Drying Platinum Concentrate by Mr. W. Grimm ......................................................... 97
A.03. Basic Hand Calculations – Bending Moment .................................................................................... 100
A.04. Basic Hand Calculations – Principal Stress ...................................................................................... 101
1.1 Introduction

The development of rotary kilns was boosted by the demand for cement from the 1960s till the 1970s [1]. In the early stages of kiln development, stationary kilns were used in order to dry limestone and chalk in order to manufacture cement. In 1885, Ransome, an English engineer, developed and patented the first slightly tilted horizontal kiln which was able to rotate and allowed material to move steadily from the inlet to the outlet of the kiln. This key principle is still in use in the rotary kiln industry today [2].

Rotary kilns are advanced thermal processing systems which are used to process solid material at elevated temperatures. Rotary kilns are used for different processes such as calcination, thermal desorption, organic combustion heat setting, sintering, reduction of oxide ore, recovery of hydrated lime, calcining of petroleum coke and hazardous waste recovery of hydrated lime [1] [3]. Rotary kilns were originally used in the cement industry, but due to their flexibility in processing, they were quickly extended to other industries. Therefore, the kiln’s design has been developed to process commodities and is also used for highly specialised processing applications. As new applications develop, more and more research and development is invested into rotary kilns due to their versatile thermal processing capabilities. Applications where rotary kilns are used, just to name a few, include mineral roasting, proppant sintering, gypsum and bauxite calcining, activated and reactivation of carbon, waste incineration, desorption of soil contaminants, catalyst activation, ceramic processing and plastic processing [3]. Rotary kilns may reach temperatures as high as 2000 K which gives a competitive advantage to commercial incinerators of organic wastes and solvents [1].

Rotary kilns operate by holding the processed material at a specific temperature for a specific amount of time. The temperature profile and retention time are determined through chemical and thermal analysis of the processing material. This allows process experts to know at what temperatures the processed material will react. The main component in rotary kilns is the rotating cylinder. The cylinder is sized in relation to the time, temperature and required effective heat transfer surface area for efficient thermal processing. The cylinder is set at a specific angle to allow the material to move through the drum [4].

There are two main types of rotary kilns which are the direct fired and the indirect fired rotary kilns. In direct fired rotary kilns, the processed material is in direct contact with the processing combustion gas and flame, whilst the indirect fired kiln is where the process material is isolated from the processing combustion gas and flame. In this case, the material is heated through contact with the conductive cylinder which is heated externally by the flame. Rotary kilns may be designed either in co-current or counter current configuration. These design aspects refer to the direction of the airflow relative to the material [4].

Rotary kilns may be considered as beams supported at different points along its length [4]. Even though rotary kilns have advantages, the operation of rotary kilns is not without problems. Common problems include dust generation, low thermal efficiency, non-uniform temperature distribution and non-uniform product quality [1]. The temperature profile in rotary kilns poses significant challenges in the structure of the rotary kiln. The design and maintenance of the rotary kiln needs to keep distortions of the structure to as small as possible. As the kiln rotates, it experiences flexure which
causes reduction in life of the refractory lining and causes fatigue in the shell [4]. The mechanical 
deformations which rotary kilns experience include [4]:

1. Bending of the kiln due to gravity:
   1.1 Axial distortion: The tendency to sag between tyre supports
   1.2 Transverse distortion (Ovality): Tendency of the kiln to flatten, mainly at the position 
      of the support rings

2. Distortion due to damage:
   2.1 Blistering: Due to local over heating
   2.2 Necking or waisting: Due to shell expansion beyond the limit of tyre clearance. This 
      usually occurs if the shell temperature rises more than 180 °C above the design 
      temperature
   2.3 Banana distortion: Usually due to overheating on one side of the kiln during a crash 
      stop

3. Structural defects:
   3.1 Misalignment: Vertical displacement of the rollers from their set positions
   3.2 Kinks and dog legs: Off axis defects during assembly or maintenance of the shell

4. Torsional distortion: Twisting of the shell caused by the torque of the drive. This mechanical 
deformation is considered to be a minor problem

5. Thermal expansion: Due to the high temperatures, the kiln expands radially and longitudinally. 
   Radial expansion causes the clearance between the support rings and shell to decrease, while the 
   clearance between the shell and the brick lining increases. Longitudinal expansion affects the 
   location of the support rings with respect to the rollers. To minimise this effect, kilns have been 
   designed to allow significant axial expansion.

Figure 1.1 illustrates the main forms of mechanical deformations that occur in rotary kilns. Testing is 
required on pilot plants to examine how different process materials react to certain temperatures and 
different retention times to achieve the desired outcome. Different temperatures and times have a 
direct influence on the structural stability of the rotary kilns and how they operate [4]. In order to get 
a better understanding of the structural integrity and the problems faced when dealing with direct 
-fired rotary kilns, a pilot plant developed by Drytech International Pty. Ltd. at their facility in Denver, 
Johannesburg will be investigated.

Figure 1.1: Common Mechanical Deformations of Rotary Kilns a) Ovality b) Necking c) Axial Distortion d) Blistering e) Banana 
Distortion [4]
Drytech was established in 1981 by Harry Traub in order to provide tailored drying solutions for the mineral, chemical and food industries [5]. The company’s focus extends from pilot plant development and testing through to turnkey installations. In the past 30 years Drytech has developed a wealth of in house expertise along with an extensive laboratory and pilot plant facility, where research and development is continuously being done in order to improve existing technologies and where new developments are being tested. The equipment and services which Drytech offers include calciners, conveyor dryers, flash dryers, fluid bed dryers, fluidised bed combustors, rotary dryers, spray dryers and vacuum dryers. The industries which Drytech render their services to include mining and minerals, food, biomass, fine chemicals and polymers, web and textiles [5].

Drytech’s mission target profile is that of a dominant and cohesive engineering business specializing in manufacturing and committed to industrial engineering industries. They provide services and technology which are at the lead of both process efficiency and environmental responsibility. They are dedicated to producing high calibre, cost effective eco-friendly engineering solutions [5].

1.2 Problem Statement

1.2.1 Motivation

Rotary kilns experience a number of mechanical deformations during operation. There is limited knowledge on the structural behaviour of such systems during operation. Design optimization requires detailed knowledge of the structural performance of the kiln given the range of operating temperatures and fill percentages. Therefore, there is a need to better understand the structural response of the kiln during operation, and to develop numerical models that could be used for design optimisation. Due to the nature of kilns, high temperature fluctuations are experienced, which complicate the modelling of the structural behaviour of the system. Furthermore, there is limited contemporary literature covering the modelling of the structural performance of such industrial equipment.

1.2.2 Aims

The aim of this investigation is to develop a validated numerical model to study the structural performance of a directly heated rotary kiln during transient operation for different load scenarios.

1.2.3 Objectives

In order to achieve the stated aim of the work, the following should be met:

1. Gather information on the current state of knowledge on kiln technologies, and the major analysis challenges in modelling transient behaviour.
2. Design and conduct experiments to determine the transient thermal and structural response of the direct-fired kiln for selected operating parameters.
3. Develop a validated numerical model to study the transient structural behaviour of the kiln.
4. Use the validated model to study the transient structural behaviour of the direct heated rotary kiln.
5. Analyse the obtained data and deduce conclusions on the obtained results.

1.3 Scope of Work

The investigation will be limited to a laboratory scale direct heated rotary kiln manufactured by Drytech International Pty. Ltd. Measurements will be limited to solid mass flow rate, air mass flow rates, temperatures at inlet and outlet and outer casing strains at specific points around the circumference of the directly fired rotary kiln pilot plant. The numerical modelling of the structural response of the kiln will be done using the commercial finite element method (FEM) software Abaqus 6.14.

1.4 Research Methodology

The purpose of the work was to develop a validated transient numerical model of a direct-fired rotary kiln pilot plant. The following work allowed accurate assessment of the structural performance of such systems.

Experimental measurements were done in winter, at the Drytech International direct-fired kiln pilot plant facility. Special care was taken to capture the worst case loading scenario. Experimental data was captured by recording the kiln shell strain response at a selected point and temperature readings were recorded on the outer surface of the kiln shell and the inside surface of the internal fire brick lining. The strain gauge was stuck onto the outer shell of the direct-fired rotary kiln pilot plant, in the centre between the two support rider rings. The strain gauge rosette was specifically used to investigate circumferential and longitudinal stresses on the surface of the kiln. K-type thermocouples where equi-spaced along the length of the kiln, on the outer shell and 5 mm from the inner surface of the refractory lining. The recorded temperature variations will be correlated back to the experimental stress to investigate the structural performance of the direct-fired rotary kiln.

Strain measurements were captured for three scenarios i.e. (1) kiln rotation under its own weight (2) kiln rotation with added weight and without heat generation and (3) kin rotation with added weight and heat generation. The experimental strain data was used to calculate the experimental principal stresses.

The maximum principal stress data, for one rotation, was used to validate the transient numerical model.

A transient model was developed to model the heat transfer of the system during operation and to investigate the structural behaviour of the kiln for different load cases. An optimisation study was conducted to investigate the influence of fill percentage and increased system temperature on the structural behaviour of the thermal processing system.
1.5 Concluding remarks

Chapter 1.0 presented the background to the research topic and identifies key elements which will be investigated. The aims and the objectives are clearly described. The scope limitations and methodology of the work were outlined.

Chapter 2.0 presented the theory related to direct-fired rotary kilns that was relevant to the current study. The theory includes a basic description of different types of kilns, added systems and different processes associated with kilns. A more in depth look into heat transfer modes were investigated in order to understand the thermal response of the rotary kiln during operation. Finite element models on direct-fired rotary kilns were researched in order to gain a better understanding of the process, improve on previous research and to develop a working and accurate numerical model of the structural response.

Chapter 3.0 presented the experimental set up and procedure which was used and designed to capture the actual performance of the selected pilot plant rotary kiln for typical operating temperatures.

Chapter 4.0 presented the results obtained from the experimental analysis. Measured strains were converted to stresses which were used to assess the structural performance of the selected direct-fired rotary kiln for different load cases.

Chapter 5.0 presented the transient numerical modelling of the direct-fired rotary kiln. The validation of the numerical model using experimentally determined data is also presented. The model is then applied to performance assessment of the direct-fired rotary kiln.

Chapter 6.0 presents the conclusions and recommendations arising from the investigation.
CHAPTER 2.0: LITERATURE REVIEW

2.1 General Remarks

Chapter 1.0 introduced the investigation by identifying typical problems associated with direct-fired rotary kilns. This chapter presents an in depth literature study concerning direct-fired rotary kilns in order to understand the process and equipment better and to determine the problem areas which previous researchers encountered in terms of numerical modelling. The topics covered include the development of kilns; directly fired rotary kilns; performance of directly fired rotary kilns; and structural numerical analysis of directly fired rotary kilns.

2.2 Background into the Development of Kilns

The Development of Portland cement involved the burning of finely ground chalk with finely divided clay in a lime kiln which yielded carbon dioxide as an off-gas. Stationary kilns were used in the early stages of development of Portland cement and it was found that the sintered product was wastefully allowed to cool after each burning before grinding. Thomas Millen and his two sons experimented with burning of Portland cement in a piece of sewer pipe which gave rise to the development of the first experimental rotary kiln used in America [2]. Earliest types of kilns were nothing more than a shallow pit which was dug in the ground. The development of kilns occurred in number of stages. The beehive kiln was the first of many developments. A burning chamber with holes for heat to rise was built under a brick enclosed chamber where clay pottery was laid. Another development used a chimney stack to improve the air flow which allowed the fuel to be burnt completely at higher temperatures [6]. The Romans designed climbing kilns which were built on a slope so that the fire could be lit from the bottom therefore, allowing the heat to rise up naturally and thus allowing a more consistent heat control. This type of kiln allowed more pottery to be fired at the same time than the single chamber beehive kiln [7]. Updraft kilns were developed in Japan where the kiln consisted of multiple chambers and the heat would travel upward in the first chamber, then downwards and upwards and downwards again into the second, third and fourth chambers respectively. This type of kiln allowed greater production rates of pottery. Since then, modern technology has allowed for more efficient electric, natural gas or propane fired rotary kilns [8].

The kilns design either allows the material to be in direct contact with the heat source or in indirect contact with the heat source. Additionally, there are two types of categories that kilns fall under; either intermittent or continuous. Intermittent kilns are stationary kilns. The kiln is loaded, sealed and then the temperature within the kiln is allowed to rise and then gradually decrease. After the firing process, the kiln is cooled and emptied. Continuous, usually referred to as tunnel kilns, are long tunnel structures where only the middle section is directly heated. From the cool entrance, material is slowly fed into the kiln and is transported through the structure where the temperature slowly increases until the material reaches the centre. The material is then transported through the rest of the structure allowing the material to be slowly cooled as it exists on the other end of the kiln. The different type of kilns include [9] [10]:
CHAPTER 2.0: LITERATURE REVIEW

1. Bottle kiln: Type of intermittent kiln which is coal fired, surrounded by a tall brick cone in the shape of a bottle neck.
2. Top hat kiln: An intermittent kiln where the pottery is placed on a heat slab and covered by a box shaped cover.
3. Electric kiln: Where the Kiln’s heat source is electrical.
4. Car kiln: An intermittent kiln where the bottom of the kiln is mounted on a rail cart. Once the process of the kiln is completed, the cart is detached from the kiln and another cart rides in below it and the kiln is then lowered down onto that cart. The process is repeated.
5. Modern kiln: Uses control systems which allow adjustment of temperature in the firing cycle.
6. Microwave assisted firing: This type of kiln combines microwave energy with different types of energy sources such as radiant gas or electric heating.
7. Rotary kilns: There are two types of rotary kilns; directly fired and indirectly fired kilns. Both kilns are under the continuous category, where a tunnel shaped chamber rotates about its axis. Indirectly fired kiln is where the heat source does not come into contact with the material, and directly fired kiln is where the material is in direct contact with the heat source.

2.3 Directly Fired Rotary Kilns

2.3.1 Introduction to Directly Fired Kilns

One of the most important uses of rotary kilns is to manufacture cement. Portland cement clinker is manufactured by burning and grinding a mixture of limestone and clay or limestone and shale and was first developed in 1842 in a static lime kiln. A conical or beehive chimney was added to the traditional egg-cup shaped lime kiln. The design was limited by its size since it was only able to produce 30 tons of clinker a week. Around 1885 a continuous firing kiln was made which allowed continuous production of cement clinker. A shaft kiln, similar to a blast furnace, was built on a slant. It allowed the feed material and the fuel to be continuously added on top, then sintered and dropped out a hole at the bottom. This design of kiln was then replaced by the rotary kiln which rotated as it was burned for more efficient production. Nowadays rotary kilns contribute to more than 95% of the world’s production of cement clinker. A typical rotary kiln is able to produce 100 to 200 tons per day [11].

Rotary kilns may be seen as heat exchangers where energy from hot gases are absorbed by the bed material, refractory lining and shell. As the gas moves through the kiln, the refractory lining within the direct fired rotary kiln undergoes different types of heat exchange processes such as drying, heating and chemical reactions. The most common type of rotary kiln is when there is direct contact between the gas and the insulation material or bed material. This type of rotary kiln is known as a directly heated rotary kiln [2]. Direct fired kiln’s ability to maintain high production rates puts it in an economical prominent position for calcining materials at high temperatures. Directly fired kilns operate in industry for 24 hours a day 330 days a year. Rotary kilns are usually fired in counter flow. Parallel flow kilns exist and are used in processes where the feed releases volatiles that can be burned within the kiln [12]. Figure 2.1 illustrates a typical counter flow directly heated rotary kiln, where the flow of gas is opposite to that of the material flow. There are different types of direct fired rotary kilns that are used in industry, namely wet kilns, long dry kilns, short dry kilns and indirect fired kilns [2].
2.3.2 Different Forms of Rotary Kilns

Wet kilns are used when slurry material is fed into the kiln. The inlet of the kiln uses chains to recuperate heat in the exhaust gas to preheat the feed and reduce energy wastage. The chain is used to break up the feed material when the material is in the transition phase as it changes from slurry to solid. In long dry kilns, preheating, drying and calcination all take place in one vessel. These type of kilns are used when the feed material consist of large particles. The feed into these type of kilns is usually dry, as compared to wet kilns. Short dry kilns come equipped with external preheaters or a pre-calciner. With the external equipment the feed is dried, preheated and partially calcined before it enters the kiln [2]. Applications where the directly fired rotary kiln is used include calcination, reduction, controlled oxidation, carburization, solid-state reactions and purification [2].

Indirect fired kilns are kilns which are heated externally. These types of kilns are used when the direct contact between the feed material and the heated gas is not required, or not feasible due to the process material characteristics. Externally heated kilns have a low thermal efficiency, therefore they are small compared to directly fired kilns. A special feature of indirect heated kilns is that they consist of multiple and compartmentalised temperature control zones which allow heating by electricity or by gas. Therefore, these types of kilns are able to reach high temperatures of approximately 2400 °C [2].

All types of rotary kilns are widely used for cement, metallurgy, chemicals and other industries since they are able to mix the process material within the kiln efficiently due to their heat transfer capacity [13].

2.3.3 Design and Application

The direct fired rotary kiln is a refractory lined inclined cylinder which rotates and conveys material that is in direct contact with products of combustion generated by a heat source found at one end of the cylinder. The kiln consists of a steel cylindrical shell supported as a continuous beam by rider rings or tyres. Each ring is supported on two rollers, or trunnions, which consists of journal bearings that are heavily loaded, which allows the rollers to rotate about their respective axis. The bearings are mounted on steel frames to ensure alignment and to form a support station. The number of rings and support stations is dependent on the diameter, length, shell thickness and weight of the kiln. The support stations are carried on reinforced concrete piers [12]. Figure 2.2 illustrates a typical directly fired counter current rotary kiln. Figure 2.2 illustrates each mechanical component that makes up a directly fired rotary kiln.
2.3.3.1 Drive Mechanisms

A pair of thrust rollers are used on the tires in order to limit the kiln’s axial movement due to the slope and weight, rotational forces, thermal expansion or misalignment. Rotation of kilns is accomplished by a ring gear/pinion arrangement including a gear reducer and an electric motor. Kilns are provided with a speed controlling device such as a DC drive motor, eddy current coupling or multi-speed AC motors. Some industrial kilns operate with dual drives using two pinions, reducer and motors at one ring gear. The ring gear is located at the cooler end of the kiln and is designed to incorporate a service factor of 1.5. Emergency drives are used to ensure rotation at least every 15 minutes, to prevent shell distortion in the event of power failures [12]. Figure 2.3 depicts a typical arrangement of the thrust rollers.
There are two different driver mechanisms which rotate a rotary kiln, namely a chain and sprocket or a gear drive. For both arrangements, there are two support rider rings on the rotary drum that are placed on top of the trunnion wheels, where at the point of contact, the rotary drum is supported [15].

The chain and sprocket arrangement is similar to how it works on a bicycle. A large sprocket is wrapped around the drum with a chain that goes to the reducer and motor. The motor turns a gear box which turns a small sprocket that is attached to the other end of the chain. The gear drive is best suited for heavy duty situations, running at 55 kW [15].

The gear system is similar to that of the chain and sprocket arrangement, the only difference being that there is no chain mating the larger gear and smaller gear on the motor. This type of arrangement is called the girth gear drive. A large gear surrounds the rotary drum shell and meshes with the smaller pinion gear on the motor [15].

2.3.3.2 Shell

The shell of the kiln is typically manufactured of hot rolled carbon steel plate ASTM A36, A283 or A285. Shell temperatures increase toward the firing end, which usually exceeds 370 °C. The ends of the shell that are exposed to temperatures too high for carbon steel are shielded with segmented alloy nose ring casting. The shell of the kiln terminates in a stationary housing at each end. Seals are incorporated into the design to limit the admission of leakage air at each housing. In the counter flow case, the burner is mounted in the discharge end housing called the firing hood. The seals found at this end improve fuel economy by preventing ingress air from ambient. The seal at the feed housing reduces infiltration to minimise the size and power requirements of the exhaust system. If seals are not used correctly, then the gas flow rates are doubled compared to the flow resulting from combustion. Correctly used seals limit the air ingress up to 10 to 15% of total flow [12].

Containing the appropriate temperature within the rotary kiln is what allows the desired chemical reaction to occur. Sustaining that temperature becomes a difficult task if the right seal is not used. Almost every rotary kiln runs at a slightly negative pressure, which means the gas is drawn out of the system rather than being drawn into the system. Since kilns operate at higher temperatures than the ambient air, air which leaks into the rotary kiln will cause the temperature inside the kiln to drop. This will result in an unnecessary amount of energy usage and wastage which decrease the thermal efficiency of the system. If the leak is too great it could disrupt the chemical reaction [15].

2.3.3.3 Seals

Sealing the ends of the rotary kiln may be difficult to achieve, since there will always be something rotating that is in contact with something that is stationary. Leakages commonly occur at these stationary parts. A way in which this problem may be overcome is by using a leaf seal or labyrinth seal [15].

Leaf seals have a similar appearance to a deck of cards which are fanned out. The leaves of the seal are made of spring steel. The leaves are bolted to the stationary equipment, which force the leaf seals to push against the seal/wear plate of the rotating kiln. This arrangement maintains the pressure...
within the kiln to create a good seal. If maintaining atmospheric pressure within the kiln is of utmost importance, a double purged leaf seal may be used [15]. Figure 2.4 illustrates the mounting of a single leaf seal.

![Figure 2.4: Single Leaf Seal Arrangement [15]](image)

Double purged leaf seals may be used, for example, if the atmosphere within the kiln cannot tolerate oxygen from the leaked in air. The purged double leaf seal is made of two components. The first component comprises of two sets of seals which consists of two layers of leaves laid on top of each other. The second component is an inert purge gas, such as nitrogen, which is introduced between the two sets of seals. The gas pushes outward to ambient so that there is a flow of gas outwards instead of inwards to the interior of the rotary kiln shell [15]. Figure 2.5 illustrates a typical arrangement of a double leaf seal.

![Figure 2.5: Double Leaf Seal Arrangement [15]](image)
Labyrinth seals are cost effective seals when air leakage is a major concern. The seal provides a difficult path for the ambient air to pass through by means of a relatively close clearance between the rotating seal and stationary housing. Figure 2.6 illustrates the arrangement of a labyrinth seal.

![Labyrinth Seal Arrangement](image)

2.3.3.4 Refractory Lining

The refractory lining in the kiln reduces the kiln’s heat losses and protects the shell from excessive temperatures and from abrasion of the tumbling charge material. The refractory lining consists of alumina-silicate refractories applied either in brick or cast form. The brick life is affected by fluctuations in flame length, fast start ups and fast cooling which causes coating to fall off along with some brick material [12]. The type of refractory used in the kiln is dependent on rotary kiln temperature, material chemistry and the abrasiveness of the material being processed [15].

Cast-able refractory comes in a powder form and is mixed with water on site. Before the mixture is put in place, Y-shaped anchors are installed which are similar to rebar which is used to reinforce cement. The purpose of Y-shaped anchors is to reinforce the mixture. Once the anchors are in place, the mixture is pumped into the lining of the kiln and allowed to settle for a couple of days. Cast-able lining is susceptible to installation problems. Downtime is minimised when using cast-able refractory since the problem area may be cut out and new refractory may be poured back in the cavity [15].

Brick refractory quality is measured by the percentage amount of alumina. Alumina gives the refractory its durability in terms of thermal resistance and strength. If the process material is abrasive, it is recommended that brick refractory is used since it is more durable than cast-able. A problem arises when using brick refractory. Since bricks rely on the pressure of their neighbouring bricks, one brick cannot be simply replaced when failure occurs rather a whole section of the refractory needs to be replaced [15].
If the kiln experiences large magnitudes of temperature, then it is advised that multilayers should be used in the refractory such as the working layer and the insulating layer [15]. The working layer is in direct contact with the process material. The working layer is a dense lining to withstand high temperatures and abrasion. In terms of refractory, the denser the lining the less insulating ability it contains. Therefore, there is a need for an insulating layer. The insulating layer’s purpose is to insulate the shell of the rotary kiln so that the high temperatures cannot reach the kiln shell or damage it [15]. Figure 2.7 a) shows the typical layers in a rotary kilns using cast-able insulation and Figure 2.7 b) illustrates the rotary kiln layers using brick lining.

Figure 2.7: a) Cast-able Refractory Lining b) Brick Refractory Lining [15]

A significant source of refractory failure is thermal cycling. Thermal cycling occurs when the rotary kiln is heated and then cooled. Each time the kiln is heated and cooled, the kiln shell and lining experiences differential straining. This causes stresses to occur in the refractory lining which may cause cracks. Another reason for refractory failure is chemical composition of the process material. Chlorides usually damage refractory lining. Chlorides attack the refractory which causes excessive wear because of the chemical’s corrosive nature. To spot for damage of refractory, a temperature gun could be used to identify the hot spot if one occurred. The temperature should be the same for the entire circumference of the shell. There should also be a gradual shift in temperature from one end of the kiln to the other and not a drastic change [15].

2.3.3.5 Separate Components of Directly Fired Rotary Kilns

Most rotary kilns are designed to obtain maximum mixing of material and gas and optimal heat transfer to obtain optimal product quality. There are different components which are added to form the entire system for optimal efficiency of the rotary kiln for material processing. To make the kiln as efficient as possible, heat recuperators such as preheaters are added. The preheaters allow energy to be recovered from the exhaust gas to preheat the feed material before it enters the kiln. Coolers are
added to the kiln in order to cool the material for safe material handling and to recuperate the energy to preheat the combustion air [16].

Mixing in kilns is accomplished by the rough refractory surface which lifts the charge to its angle of repose. Mixing is further improved by adding internal equipment such as lifters, chains, trefoils and metallic quadrants. Another factor which affects the mixing process is the particle size. Large particles are heated more thoroughly than fine particles. Muds, filter cakes and slurries with precipitated solids are mixed well with the use of lifters and chains. Mixing of such materials is further improved by the pelletizing action within the kiln during the drying process [12].

The end at which the feed is introduced is called the feed hood. The feed is usually fed through a feed chute. Muds and filter cakes enter through screw conveyors. Liquid or slurry feeds are usually pumped into the kiln. Uniform feed rates and moisture contents are important to a rotary kiln’s success. Without lifters and/or chains, the kiln is a poor dryer depending on the process material [12].

2.3.3.6 Chemical Process Operation

Direct fired rotary kilns are fired either by gas, oil, coal or a combination thereof. Burners usually penetrate within the shell to approximately 0.3 meters. Oil and gas burners accomplish the task of mixing fuel with air in order for combustion to occur. Pulverised coal is typically used in the cement industry and in the dead burned dolomite operations where high temperatures are required. Burner flames are developed within the kiln, but some designs have separate combustion chambers where the flame develops to a desired temperature before entering the kiln shell. Separate stoker fired grates may also be used to burn lump coal to form carbon monoxide and hydrogen to fuel the rotary kiln [12]. Possible ways in which fuel economy may be improved include the following techniques [12]:

1. Remove the sensible heat to heat the air needed for combustion
2. Reduce radiation loss per ton of product
3. Reduce quantity and temperature of exit gas
4. Reduce moisture of the feed material

For most kiln applications, the purpose is to drive the required bed reaction, either by kinetic or thermodynamic reactions, which requires high bed temperatures. In the case of directly fired rotary kilns, the energy required to raise the bed temperature to the required temperature for the reaction to occur, originate from the burning of hydrocarbon fuels in the freeboard near the heat source or burner [17]. The energy is then transferred by the gas phase and the bed as shown previously in Figure 2.1.

The different heat transfer mechanisms which occur within the directly heated kiln include conduction, radiation and convection. Conduction and radiation occurs between particle to particle and partial to surface and convection occurs between gas and particle. Another heat transfer mechanism occurs when the particles move within the kiln. The movement of the particles is in the transverse plane, and dependent on the rotational speed, the rate at which the material is fed into the kiln and the rheological properties of the feed material [18].
2.4 Performance of Directly Fired Rotary Kilns

2.4.1 Heat Transfer Mechanisms

2.4.1.1 Convection

Convection heat transfer occurs between a solid surface and a fluid which moves and comes into contact with the surface. The rate of heat transfer between a surface at a temperature \( T_w \) and a fluid at temperature \( T_f \) can be calculated from Newton’s law of cooling which may be expressed mathematically as [19]:

\[
Q = hA(T_w - T_f)
\]  

where \( Q \) is the heat convection in W; \( h \) is the heat transfer coefficient in \( \frac{W}{m^2\cdot\circ C} \); \( A \) the surface area of the body in \( m^2 \); \( T_w \) is the surface temperature in \( ^\circ C \); and \( T_f \) is the fluid temperature in \( ^\circ C \) [19].

Even though equation 2.1 might seem simple, but determining “\( h \)”, the heat transfer coefficient, is where the complexity comes in. The heat transfer coefficient is a complicated function of the flow and the thermo-physical properties of the fluid such as the viscosity, density and the dimensionless relationships such as the Reynolds number, Prandtl number and the ratio of the momentum diffusivity to the thermal diffusivity [19].

There are two different forms of convection namely free and forced convection. Forced convection is where the flow of the fluid is driven by a fan, a pump or some external system which forces a flow over a surface. Free convection is where the flow is driven by temperature induced density variations in the fluid such as buoyancy or a combination thereof [19].

2.4.1.2 Conduction

The shell and refractory walls of the kiln possess molecules which make up the rigid lattice structure. The molecules contain internal energy in different forms such as vibrational and rotational kinetic energy. If a temperature difference occurs within the material, then energy will be transferred by molecular interaction from the molecule with the higher energy to the molecule with lower energy. The rate at which energy is transferred is dependent on the temperature gradient and the mode of interaction. In other words, Fourier’s law of heat conduction. Fourier’s law states that the heat flux by conduction across a plane perpendicular to another reference plane is proportional to the temperature gradient. Fourier’s law is given mathematically by equation 2.2 [20]:

\[
q_x = -kA \frac{\partial T}{\partial x}
\]  

where \( q_x \) is the heat transfer rate due to conduction and given in W; \( k \) is the thermal conductivity in \( W/m\cdot^\circ C \); \( A \) the surface area of the body in \( m^2 \); and \( \partial T/\partial x \) is the temperature gradient in the direction of heat flow [20].
2.4.1.3 Radiation

Heat transfer by radiation does not necessarily require a medium. Thermal radiation is the energy emitted by a body solely due to the temperature of the body and at a frequency that falls within a small portion of the electromagnetic wave spectrum. When radiation is reflected on a homogenous body, some of the radiation is emitted and the rest of the energy penetrates into the body. The radiation gets absorbed as it travels through the medium. If the thickness of the body allows transfer of energy such that some of the radiation is transmitted through the body, then the transmitted radiation will appear unchanged. If the body or the material that the body is made of, is a strong internal absorber, then the radiation that does not get reflected and will be converted to internal energy within the layer near the surface. For a material to be a good absorber, the material must have a low surface reflectivity and sufficiently high internal absorption to prevent radiation from passing through it. A surface is said to be black if it has zero surface reflection and complete internal absorption [21].

A blackbody is defined as an ideal body that allows all the incident radiation to pass into it and absorbs internally all the incident radiation. This is true for all wavelengths and all angles of incidents. Therefore, a blackbody may be said to be a perfect absorber of incident radiation and in radiation heat transfer it serves as a standard with which real absorbers may be compared to. The Stefan Boltzmann Law states that the total emissive power of a blackbody is proportional to the fourth order of the absolute temperature and given mathematically as [19]:

\[ E_b = \sigma A T_{bb}^4 \]  

where \( E_b \) is the heat transfer due to radiation of a blackbody in W; \( \sigma \) is the Stefan-Boltzmann constant with a value of \( 5.669 \times 10^{-8} \text{ W/m}^2\text{K}^4 \); \( A \) is the surface area of the blackbody in \( \text{m}^2 \); and \( T_{bb} \) is the temperature of the black body in K. The total emissive power of a real surface can only be written as a ratio of the blackbody. The ratio is defined by the emissivity \( \varepsilon = E/E_b \) of the body [2]:

\[ E = \varepsilon E_b = \varepsilon \sigma A T^4 \]

The total emissive power includes all wavelengths within the thermal energy band [2].

2.4.2 Heat Transfer Mechanisms Applied to Directly Fired Rotary Kilns

Xiao-hui [22] developed a steady state numerical model to simulate the temperature field for a rotary kiln using iron ore oxidized pellets as process material. The model for the temperature field was not only based on conduction, convection and radioactive heat transfer among the flue gases, kiln bed and pellet bed material, but also included the coal combustion and analysis of reaction heat of pellet thermal treatment in the kiln. During operation, the kiln wall and pellets were heated by convection and radiation, and at the same time the pellets were heated by the wall through radiation and conduction. Thermal energy was released from the outside wall by convection and radiation. The thermal numerical model was correctly modelled to depict the temperature distribution in the kiln according to the author.

Arad [23] modelled a rotary kiln using QuickField. The FEM (finite element method) was modelled as a thermal process in a multi-layer body since it took into account the shell, chamotte, air and clinker. The model developed for the kiln was a steady state heat transfer, linear with axis symmetry model.
class. The model looked at all three heat transfer mechanisms from the combustion process and it was discovered that radiation was the main heat transfer mechanism. Two geometrical models were created. In one of the models the flame position was concentrated in the centre and in the upper half for the other model. Each model was tested and experimentally validated. Two different temperatures were chosen for the bed surface, 1450 and 1000 K respectively. From the model, it was discovered that the temperature model inside the kiln follows a parabolic function. There was a significant increase in temperature near the flame from the burner. In order to increase refractory life, the flame from the burner should never impinge on the refractory lining.

Mujumdar [24] presented a simulation on a rotary cement kiln using a one dimensional model. The work was based on a computational fluid dynamics model. The way the heat transfer was analysed mathematically is of interest. The chemical reactions which occur in the bed of the kiln is driven by the energy supplied by the free board and kiln walls. Heat transfer occurs by all three models, but radiation is the dominant mode of heat transfer. Previous work done by Gorog [25] on the heat transfer modes in kilns discovered that the radioactive transfer in the axial direction is dependent on axial flame temperature gradient, relative flame diameter (diameter of flame/diameter of kiln) and wall refractivity. It was deduced that for typical values for the mentioned parameters, temperature gradient of 100 K/m, relative diameter of 0.5 and wall refractivity in the range of 0.2 to 0.5, the maximum errors caused by neglecting radioactive heat transfer in the axial direction is less than 10%, and therefore the radioactive heat transfer mode was neglected [25]. The heat transfer modes are represented graphically in Figure 2.8.

![Figure 2.8: Heat Transfer Modes within Direct Heated Kilns [24]](image)

Where $Q_{RWB}$ and $Q_{CW_B}$ are due to radiation and conduction between the internal wall of the kiln and bed; $Q_{RGB}$ and $Q_{CGB}$ are due to radiation and convection between gas and bed; $Q_{RGW}$ and $Q_{CGW}$ are due to radiation and convection between the kiln free board gas and internal wall; $Q_{REF}$ and $Q_{STL}$ are heat transfer due to conduction in refractory and the steel shell; $Q_{LOSS}$ are the heat loss due to radiation and convection. The energy balanced across the walls of the kiln was solved in the steady state situation to calculate the respective temperatures of the system. The flame temperature within the kiln was varied and it was discovered that as the temperature increases, the clinker mass fraction at the exit increased. This was expected since more energy is added to the bed. As the bed material moves through the kiln and becomes more heated it turns into a liquid which coats the inner surface.
of the kiln. Once the coating is formed, the shell temperature of the kiln decreases abruptly. From this it could be said that the model was able to predict the behaviour of the kiln by adjusting the maximum temperature. Energy may be lost in three different ways either by un-recovered energy from hot solids leaving the kiln, un-recovered energy from the hot gases leaving the kiln or energy lost to convection and radiation. The simulation indicated that better performance may be obtained at lower RPM, higher solid flow rate and smaller tilt [24].

Ginsberg [26] developed a model of a rotary kiln for calcination of titanium dioxide white pigment. The model was capable of reproducing the dynamic behaviour of a rotary kiln with quantitative accuracy. For the simulation to be reliable, the heat and mass transfer were modelled based on the physically found relationships. The author validated the model by obtaining transient results from an industrial kiln. Heat losses from the kiln outer shell were measured by taking into account the ambient temperature and the wind velocity which were recorded at a meteorological station situated 2.3 km away from the plant. Data was recorded for 15 days and it was discovered that for the first 7 days the kiln was in a quasi-steady state. From the measured data one steady state and one dynamic test were used to validate the numerical model. The assumptions made by the author were that the gas side surface of the solid bed was regarded flat and that the gas and solids were mixed homogenously due to turbulent gas flow and solid bed circulation. From the author’s assumptions and measuring techniques, the models results were closely related to that of the measured data [26].

Alexopoulos [27] developed a simulation model for the transient process behaviour of solar aluminium recycling in a rotary kiln. The mathematical model allowed the investigation of the transient thermal behaviour of the solar heating process and to support the design of solar heated rotary kilns. The model consisted of unsteady state one-dimensional heat transfer equations for the wall elements, dynamic energy balance for the aluminium, the salt and gas hold up and extra equations for material properties and heat transfer. A finite difference approach is used for the heat transfer equations in order to resolve the space derivatives. The model was separated into three cells, namely the middle cell, first and last cell. The middle cell may be duplicated for higher resolution. The first and last cells contain a front and back wall cover. The wall of the kiln was divided into two different segments for different temperatures, a wall which is coated with aluminium and salt and a wall segment in contact with gas. The wall was divided into three parts i.e. the refractory, ceramic isolation and the steel casing. The bed was broken down into two layers. One layer was molten salt as the upper layer, which was in contact with the gas, and aluminium as the bottom layer. It was discovered that the results met expectations where higher losses and less effective heat transfer to the aluminium, since salt has a small heat conductivity, triggered a decrease in efficiency and therefore an increase in cycle duration. These results were similar to the study done by Song [28] for a gas fired plant.

2.5 Structural Numerical Analysis of Directly Fired Kilns

2.5.1 Introduction to Finite Element Analysis

The natural physics of engineering problems may be generally modelled mathematically using partial differential equations and integral equations. Analytical solutions to such models may be solved by making certain simplifications and/or assumptions. In the case of realistic modelling, the geometry or other certain features will be irregular or arbitrary and therefore no simple analytical solution can be found. In such cases numerical solutions instead of exact closed form solutions will be required. Finite
element method (FEM) was developed as a powerful numerical analysis technique for obtaining approximate solutions applicable to such problems and therefore it may be applied to a wide range of engineering problems [29].

Finite element method was developed for structural/stress analysis in complex civil and aeronautical structures. In the early 1970’s, the finite element method was limited to expensive mainframe computers which were owned by aeronautics, automotive, defence and nuclear industries. As computers become more available and affordable and their computational power increased, the application of finite element method was extended to academic research and almost all the engineering disciplines successfully make use of the method. The disciplines which frequently use the method of numerical solution include civil, mechanical and aerospace. The areas where finite element method is applied include heat transfer, fluid mechanics, electromagnetism, biomechanics, geomechanics and acoustics. Finite element method is also a powerful technique for solving problems with complicated or irregular geometries. Finite element method may also be applied to multidisciplinary problems where there is a coupling between two or more disciplines. An example would be thermal stress analysis in microelectronic structures where there is a natural coupling between heat transfer and displacements and therefore stresses. Due to the diversity and flexibility of the finite element method as an analysis tool, it is receiving increasing attention in academia and in industry today [29].

2.5.2 Basic Approach of Finite Element Analysis

The basic idea to finite element method is to discretize the domain under investigation into a finite number of elements. Therefore, the entire domain is approximated by the assembly of all these small elements. In each individual element, a system of equations with unknown field variables are developed on the basis of the governing equations from mathematical model by assuming a shape function to approximate the physical behaviour of an element. The shape functions are defined in terms of the values of the field variables at specific points called nodes. These nodes are usually located on each element’s boundary where adjacent elements are connected. An element may have boundary and interior nodes. The nodal values of the field variable and the interpolation functions of the elements completely define the behaviour of the field variable in the element. Figure 2.9 illustrates the discretisation of the domain into elements and nodes in a two dimensional plane [29].

Figure 2.9: Discretisation of a Domain into Elements and Nodes [29]
With appropriate boundary conditions, initial conditions, and loading applied to the nodes or elements, the equations of all the elements are combined together and solved simultaneously to obtain the basic nodal result. Examples of nodal results include displacements for structural analysis or temperatures for heat transfer problems. Nodal results are referred to as degrees of freedom. Based on the degrees of freedom values at each node, other derivatives of the degrees of freedom are possible such as principal stresses in structural analysis and heat fluxes in heat transfer analysis [29]. Table 2.1 lists the degrees of freedom for some analyses which are present in finite element analysis.

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Degree of Freedom</th>
<th>Derivative Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural Analysis</td>
<td>Displacement in the x, y and z-direction</td>
<td>Strains, normal stresses, principle stresses, Von Mises stress, hydrostatic stress</td>
</tr>
<tr>
<td>Heat Transfer/Conduction Analysis</td>
<td>Temperature</td>
<td>Temperature gradient, thermal flux, heat flow rate</td>
</tr>
<tr>
<td>Electric Field Analysis</td>
<td>Voltage or current</td>
<td>Electric field, electric flux density, current density gradient</td>
</tr>
</tbody>
</table>

An important consideration when solving numerical problems using finite element method is developing a stiffness matrix. For a structural finite element, the stiffness matrix contains geometric and material behaviour information that indicates the resistance of an element to deformation when subjected to loading. Such deformation includes axial, bending, shear and torsional effects. For finite elements used in non-structural analysis such as fluid flow and heat transfer, the term stiffness matrix is also used. The stiffness matrix represents the resistance of the element to change when subjected to external influences [30].

The element stiffness matrix depends on the element type and the characteristics of the element. The element matrices are usually developed by using the direct equilibrium method and work or energy methods. The simplest method to develop the stiffness matrix and element equations is the direct equilibrium method. The mentioned method is based on applying force equilibrium conditions for force-deformation relationships for each finite element. The method is easily applied to one dimensional finite elements and becomes tedious for higher order elements. For two and three dimensional finite elements, the work method is the simplest. The work method is based on the principle of virtual work [31]. Both the direct equilibrium and work method will yield the same finite element equations relating to nodal displacements as follows [31]:

\[
\{f\} = [k]\{d\} \tag{2.5}
\]

where \(\{f\}\) is the vector of nodal forces; \([k]\) is the finite element stiffness matrix; and \(\{d\}\) is the vector for the finite element nodal degrees of freedom or displacements. Equation 2.5 represents the individual element stiffness matrix and equations of each finite element of the structure. The global stiffness matrix and equations of the whole structure will now be considered. The assemblage of the global stiffness matrix and equations is accomplished by adding up and superimposing each individual matrix using the direct stiffness method, which is based on the fact that for structures in equilibrium, the nodal forces and displacements must be in continuity and compatibility in the individual finite
CHAPTER 2.0: LITERATURE REVIEW

The global finite element equation may be expressed in matrix form in equation 2.6 [31]:

\[ \{ F \} = [K]\{u\} \]  \hspace{1cm} 2.6

where \( \{ F \} \) is the assembled vector of the entire global nodal forces; \([K]\) is the entire structure or the global stiffness matrix; and \( \{u\} \) is the assembled vector of the entire global unknown nodal degrees of freedom or displacements. Equation 2.6 must be modified to account for the boundary conditions or constraints. The global matrix should be evaluated with respect to a unique generalised coordinate system. It is important to note that the global and individual matrices explained above are applied to a problem concerned with forces, strains and displacements, in other words structural analysis problems [31]. The same approach may be used for the other analyses which were listed in Table 2.1 [31]. As discussed before, modelling of engineering problems leads to ordinary and partial differential equations which are often non-linear in nature. Therefore, a number of all-purpose finite element codes were developed in order to solve non-linear problems [32].

2.5.3 Non-linear Finite Element Analysis

Nonlinear simulations may lead to solutions which are non-unique such as localisation occurring in structural applications, limit points or bifurcation. Convergence of the numerical analysis is not always obtained in nonlinear applications. Usually there is no mathematical error analysis available for nonlinear problems. Therefore, experience in nonlinear problems and theoretical background is required to fully understand the problem at hand [32]. When material properties, loadings or boundary conditions are dependent on the displacement or its derivatives, the problem is then considered non-linear [33].

Nonlinearities which occur in practical applications in civil engineering are different in nature. In steel construction, elastic-plastic analyses are required to compute the limit loads of the truss, frame or shell structures. In the case of cable construction, geometrically nonlinear effects have to be included to describe the displacements. In concrete construction or soil mechanics, complicated nonlinear material laws have to be considered for a realistic description of the engineering problem at hand. In anchoring construction, concrete and steel are highly nonlinear due to the frictional sliding of the two different material surfaces. When concrete is manufactured, heat is generated due to chemical reactions which lead, together with the change in constitutive parameters, to heat induced stresses. Therefore, this process is a thermo-mechanical coupled problem and can only be realistically modelled by a nonlinear approach [32].

Most applications in mechanical engineering can only be successfully simulated by nonlinear methods. Among these simulations are the computation of bearing capacity of rubber bearings or forming processes. All the mentioned simulations include finite deformation analysis and nonlinear constitutive equations. The numerical simulation of crash problems can be mentioned as a complex nonlinear problem which is applied widely in the automotive industry [32].

All the mentioned applications and situations require large numerical finite element models with several thousands to millions degrees of freedom. Therefore, not only the correct formulations of the problem in the continuum mechanics setting is required, but it is also necessary to provide efficient and strong methods to obtain an accurate solution [32].
CHAPTER 2.0: LITERATURE REVIEW

Solution methods should be adjusted with respect to the type of nonlinearity. The main types of nonlinearities in solid mechanics include [32] [34]:

1. **Geometrical Nonlinearity**: This nonlinearity occurs in problems which experience large displacements and rotations and have to be considered but strains are small. Geometrical nonlinearities are sufficient to predict singular points in stability analysis. Applications include structural elements such as cables, frame membranes or shells.

2. **Finite Deformation**: Occur in problems which include metal forming and/or tyre mechanics. In such problems the displacements are large and so are the strains.

3. **Material nonlinearity**: Most materials in real life possess nonlinear behaviour. Examples of such materials include visco-elastic polymers or steel, concrete and soil which exhibit elastic-plastic responses. Material behaviour is characterised by nonlinear response functions between stresses and strains or by a set of evolution equations.

4. **Stability problems**: Such nonlinearities may be subdivided in structural mechanics into two categories namely geometrical and material instability. Geometrical instability includes bifurcations such as buckling of frames or shells. It can also be connected to limit points which indicate snap-through behaviour of a structure. Material instabilities include necking or shear bands in metals and geo-materials. The origin of the instabilities lies either in the equilibrium equations or in the loss of positive definiteness of the acoustic tensor. Both instabilities react in a very sensitive way to imperfections.

5. **Nonlinear boundary conditions**: These type of problems are characterised by nonlinearities stemming from the boundary conditions and associated with contact between two or more bodies or deformation dependent loading.

6. **Coupled problems**: These type of nonlinear problems occur when different interacting fields describe a complex physical problem. Such problems include solids, heat conduction in solids or fluids. Examples of thermo-mechanical coupling include fluid-structure interactions. Problems which contain chemical reactions include heat generations and conductions and mechanical stresses have to be coupled to model the entire process accurately.

2.5.4 **Johnson-Cook Model**

The usual approach in numerical simulations is to use two different models, one showing plastic flow and the other representing fracture. The solutions to these numerical simulations may be coupled or uncoupled. To understand and describe the various occurrences which take place during ballistic penetration, the behaviour of the material under observation which under-goes an impact generated high strain loading condition needs to be characterised [35].

The characterisation includes stress-strain response at large strains, different strain rates and temperatures and accumulation of damage and the mode of failure. This type of material behaviour involving fracture is complex and difficult to describe in analytical models. Another important aspect is the physical difference between plastic flow and fracture. In ductile metals plastic flow may be viewed macroscopically as a visible shape change, macroscopically in terms of the slip lines and at the atomic level such as the movement of dislocations. It was discovered that plastic flow is driven by the deviatoric stress state within certain types of metals. The start of the damage or fracture is due to the presence of dislocations by micro defects or micro stress concentrations giving de-cohesion and subsequently nucleation, growth and coalescence of micro cracks and micro voids. The damage propagation is influenced by the hydrostatic stress state in the material. Different mathematical
models may be used to describe plastic flow and fracture, one of which being the Johnson-Cook Model [35].

The Johnson-Cook model is a coupled material model which describes viscoplasticity (rate dependent plasticity) and ductile damage. The model was developed for impact and penetration problems. The model was analytically verified by Hopperstad [36] within the framework of viscoplasticity and continuum damage mechanics which allowed for large plastic strains, high strain rates and adiabatic heating [36].

The Johnson-Cook model was developed by G.R. Johnson, who worked for the US defence systems division, and by W.H. Cook, who was part of the US Air Force laboratory [37]. The two men created a plasticity model in 1983 which is a particular type of von Mises plasticity model with analytical forms of hardening law and rate dependence. The model is suitable for high-strain rate deformation of different materials including most metals. The model is usually used and valid for adiabatic transient dynamic simulations [37].

The Johnson-Cook plasticity model equivalent flow stress is in the form of [37]:

\[ \sigma_{eq} = [A + B(\bar{\varepsilon}^p)^n][1 + Cln(\dot{\varepsilon}^*)][1 - (T^*)^m] \]  

where \( \sigma_{eq} \) is the equivalent flow stress in MPa; A, B, C, n and m are material constants; \( \bar{\varepsilon}^p \) is accumulated plastic strain and; \( \dot{\varepsilon}^* = \dot{\varepsilon}/\dot{\varepsilon}_0 \) is the dimensionless strain rate. The parameters \( \dot{\varepsilon} \) and \( \dot{\varepsilon}_0 \) are plastic strain rate and user defined reference strain rate respectively [37]. The non-dimensional temperature, \( T^* \), is given by [37]:

\[ T^* = (T - T_{room})/(T_{melt} - T_{room}) \]  

where T is the current temperature in °C; \( T_{room} \) is the ambient temperature in °C and; \( T_{melt} \) is the melting temperature in °C [35]. From equation 2.7 it can be seen that the Von Mises equivalent flow stress is a product of the three factors which represent strain hardening, strain rate and temperature [37].

Two years later, Johnson and Cook developed a ductile fracture model which included the effects of stress triaxiality, temperature, strain rate and strain path on the failure strain and is given as [38]:

\[ \varepsilon_{failure} = [D_1 + D_2exp(D_3\sigma^*)][1 + D_4ln(\dot{\varepsilon}^*)][1 + D_5T^*] \]  

where \( D_1 \) to \( D_5 \) are material constants; \( \sigma^* = \sigma_m/\sigma_{eq} \) is the stress triaxiality ratio and \( \sigma_m \) is the mean stress [38].

The stress state is an important factor to consider when determining when fracture may occur. Specifically, the stress triaxiality plays a significant role in governing the tendency for ductile fracture. Stress triaxiality is used to describe the part of the stress tensor that is hydrostatic. The stress triaxiality is defined as the ratio of hydrostatic stress to equivalent von Mises stress. This means that a stress state with high triaxiality approaches the complete hydrostatic stress while with lower triaxiality stress state the deviatoric stress dominates. From past research it was determined that increased triaxiality reduces ductility and therefore failure strain [38].

The first term in the Johnson-Cook fracture model shows that the strain to fracture decreases as the hydrostatic tension increases. The second term represents the effect of an increased strain rate on the material ductility and lastly the third term expresses the effect of thermal softening on the material ductility [38].
The fracture model assumes that damage builds up in the material during plastic straining, and that the material breaks immediately when the damage reaches a critical value. The damage has no effect on the stress field as long as fracture does not occur. In terms of the continuum damage mechanics, the stress field depends on damage and therefore damage degrades the material’s strength while it deforms. Equation 2.7 must be coupled with damage [39]:

\[
\sigma_{eq} = (1 - D)[A + B(r)^n][1 + C\ln(\dot{\varepsilon}^*)][1 - (T^*)^m]
\]

where D is the damage variable and; r is the damage build up plastic strain \( \dot{r} = (1 - D)\dot{\varepsilon} \) [35]. If the material is not deformed then D=0 and when the material has fractured D=1, therefore \( D = D_c \) [39]. The entire fracture model describes linear elasticity, initial yielding, strain hardening, strain rate hardening, damage evolution and fracture [35].

2.5.4.1 Obtaining Material Parameters for the Johnson-Cook Model

Vedantam [40] used the Johnson-Cook strength model for mild and DP 590 steels. The author determined the material constants for the Johnson-Cook model by using quasi-static and split Hopkinson techniques at different strain rates. The respective stress-strain data was obtained. The equation for the Johnson-Cook strength model is given by [40]:

\[
\sigma = [A + Be^n][1 + Cln(\dot{\varepsilon}^*)]
\]

Equation 2.11 is similar to that of equation 2.7 except that the equivalent von Mises flow stress in equation 2.11 does not take temperature into account. Material constant “A” represents a yield stress which corresponds to a 0.2% offset strain; constants “B” and “n” represent the strain hardening effects of the material and; “C” represents the strain rate. The way in which each material constant is obtained is by experimental data. Constant “A” is obtained by plotting a 0.2% offset strain on a true stress-true strain graph at a strain rate of 1/s. Constants “B” and “n” are the 10\(^{y-intercept}\) and the slope of the Log (Plastic Stress) vs Log (Plastic Strain) for the plastic region. Constant “C” was determined as the slope of the linear fit of Log (Strain Rate) vs Dynamic stress/static stress. The material constants were obtained as A= 217MPa; B= 234MPa; n= 0.643 and; C= 0.076 for mild steel. The material constants for DP590 were as follows A= 430MPa; B= 823.6MPa; n= 0.5071 and; C= 0.0171 [40].

Liu [41] performed a numerical analysis on Weldox 460 E steel and AA5083-H116 aluminium targets using a modified Johnson-Cook model. At high velocity impact, materials undergo large plastic deformation, high strain rates, adiabatic temperature rise and damage. When work is done due to plastic deformation in steels and metals, the work is converted to heat and the dissipation of this temperature is dependent on the thermal diffusion distance and varies with strain rate. In other words, at high strain rates the generated heat in the specimen remains mostly in the specimen and this condition is referred to as adiabatic heating. The standard Johnson-Cook model does not take adiabatic heating into consideration. The standard Johnson Cook model incorporates high strain rates, large strain and temperature effects. The modified Johnson-Cook Model is given by [41]:

\[
\sigma_{eq} = [A + B(\varepsilon_p)^a][\dot{\varepsilon}_p]^c[1 - (T^*)^b]
\]

The first three material parameters, “A”, “B” and “a”, describe the elastic-plastic deformation of the material. Parameters “C” and “b” represent the strain rate and temperature effects. There are three important steps to take in order to determine and calculate these five material parameters. Material
parameters “A”, “B” and “a” are determined from a quasi-static tensile test of a smooth specimen at room temperature through the least square method. The strain rate parameter “C” is determined from stress strain plots at room temperature at various strain rates. By using the least squares method, “C” values are evaluated for each plastic strain. Lastly, the parameter “b”, which is a function of temperature, is determined from a stress strain curve at higher temperatures [41]. Liu found that the respective material constraints for the Weldox 460 steel were A=503 MPa; B=581 MPa; a=0.481; C=0.01; b=0.94; T_M=1800 K and; T_r=293 K [41].

Li [42] did research on constitutive relationships of hot stamping boron steel based on the numerical analysis of the modified Arrhenius and Johnson-Cook model. From past research, it was found that flow stress in steels and metals is affected by the deformation temperature, stress rate, strain, inner microstructure and chemical composition of the material. The Johnson-Cook model which considers the effect of strain strengthening, strain rate strengthening and temperature softening on the materials yield strength is widely used to describe the deformation behaviour of all crystalline structures. The following equation describes the Johnson-Cook model used in the research [42]:

\[
\sigma_{eq} = [A + B\varepsilon^n][1 + C\ln(\dot{\varepsilon}^*)^m][1 - D(T^*)^k]
\]

2.13

The parameters of the strain strengthening were determined at room temperature at a strain rate of 0.01 for the quasi-static test. The equation below was used to determine the material parameters “A”, “B” and “n” [42]:

\[
\sigma = A + B\varepsilon^n
\]

2.14

The least square method was used to fit the plastic deformation data of the stress strain curve at the said temperature. Parameters for the strain rate strengthening was determined using [42]:

\[
\sigma/(A + B\varepsilon^n) - 1 = C(\ln(\dot{\varepsilon}^*)^m)
\]

2.15

Since “A”, “B” and “n” have been solved, the regression analysis was used to analyse the experimental data at room temperature and at various strain rates. Material parameters “D” and “k” for the temperature softening were determined by the following expression [42]:

\[
1 - \sigma/[A + B\varepsilon^n][1 + C\ln(\dot{\varepsilon}^*)^m)] = D(T^*)^k
\]

2.16

The regression method was used to analyse the experimental data at varying temperatures and at different strain rates. From the results it was determined that equation 2.14 fit well with the experimental results, but equations 2.15 and 2.16 did not and showed a significant experimental error when compared to the experimental results [42].

Banerjee [43] determined the Johnson-Cook material and failure material constants and numerical modelling from Charpy impact test on armour steel. The behaviour of materials under dynamic loading differs significantly from quasi-static loading due to the effects of inertia, stress reflection and rate sensitivity of the material. The Johnson-Cook material model is a popular constitutive relation for metals in simulating impact and penetration related problems. The experimental material constants which were determined were used in Abaqus-explicit to simulate the Charpy test and was then compared with experimental results. Four types of tensile tests were done in order to determine the material constants for the material and failure models. The tests were done at a low strain rate and at room temperature to determine the elastic constants, initial yield stress “A” and the hardening parameters “B” and ”n”. Tests were then performed at a long slender sample at varying strain rates to determine the material model constant “C”. Lastly, tests were performed on cylindrical specimens at a constant strain rate and elevated temperatures to determine the thermal softening constant “m”.

25
CHAPTER 2.0: LITERATURE REVIEW

Banerjee determined that the material constants for armour steel were as follows: \( A = 980 \text{ MPa}; B = 2000 \text{ MPa}; n = 0.83; c = 0.0026 \) and \( m = 1.4 \). It was determined that the numerical model done in Abaqus-explicit at different strain rates and temperatures produced results which closely matched the experimental data, and therefore validating the model constants.

2.5.5 Finite Element Analysis Approach to Directly Fired Rotary Kilns

Factors which contribute to determining the life span of the lining include ovality of the steel casing, burner conditions, how the rider rings are mounted on the shell and alignment of the kiln. Unhealthy load peaks are caused when the ovality of kiln is too high. Critical temperature peaks which lead to mismatched thermal expansion are due to misaligned burner or badly controlled power output. If the riding tyre is too tight on the outer casing, this can lead to thermal expansion of the lining which leads to failure of the lining or failure of the leading tyre. Misalignment causes unnecessary stresses to the rollers, tyres and the lining. Failed lining may lead to formation of hot spots on the steel casing. The hot spots may permanently damage the casing by causing cracks, which may be followed by corrosion. During the operation of the kiln, namely start, stop and rotation, the steel casing and the lining are subjected to radial and longitudinal bending, vibrations and torsion [44].

As the kiln is heated and rotated during production, the kiln experiences complex stress/strain conditions. The amount of stress or strain the kiln may experience is determined by the state of refractory lining according to Ramanenka [44]. Once the lining within the kiln is damaged and therefore unable to protect the outside shell or casing from heat, the process is shut down and leads to production losses. There have been improvements from the early developed rotary kilns, where the expected life span of the linings was 10 to 15 days, to the newest lining developments where the expected life span has increased to approximately 200 to 300 days. Despite these growing improvements, there is still little knowledge of the mechanisms of failure. Since it is difficult to study and observe the kiln due to the sheer size of the system as well as the harsh environment it operates in. Part of the identified problem may be analysed using computational procedures to simulate the behaviour of the rotary kiln. In this case there is a contribution which may be made [44].

Del Coz Diaz [45] describes the tasks involved in the design and finite element analysis for a wet cycle cement rotary kiln. The procedures followed was a structural model of the rotary kiln by finite element method of a reduced model; static nonlinear analysis of a full model; dynamic linear analysis of a full model; and a structural verification according to ASME (American Society of Mechanical Engineers) and AD-Merkblatter rules. The investigation was based on a wet process direct fired rotary kiln. The reduced model’s purpose was to develop enough knowledge regarding contact between the shell and the tyres and between the tyres and the rollers, as well as to consider the convergence process related to the finite element mesh refinement. Ansys was used to develop the model. The kiln’s components material properties were modelled as isotropic, linear and elastic temperature dependent. The kiln boundary conditions included constraint of rotation, pairs of nodes corresponding to the tyres and kiln body was coupled in the longitudinal direction and the tyre was constrained in the z-direction. Load cases that were applied to the analysis of the kiln included body loads (refractory bricks and chains), material weight, crust from the clink added to the refractory, gravity acceleration in the static analysis and operating temperature throughout the kiln. The bed material in the rotary kiln was modelled at 20° due to the rotation of the kiln. Stresses developed in contact and ovalization of the kiln body were of most concern of the analyses. The Tresca failure criteria was used and ovalization was determined by the following equations:
\[ O_v = \frac{4}{3}(O_D)^2 \Delta H \]  
\[ O_v = 2((D_{\text{max}} - D_{\text{min}})/(D_{\text{max}} + D_{\text{min}}))100 \]

where \( O_D \) is the outside diameter in mm; \( \Delta H \) is the radial displacement in mm; and \( D_i \) is the inner diameters measured at 90° in mm. Acceptable ovalization is 10% of the nominal diameter [46].

In the case for the full model, the rotary kiln was analysed at different positions to simulate the rotation of the kiln during operation. Each position consisted of a rotation of 30° about the kiln axis. Thermal load was considered variable and the model was simulated structurally. For the full model a nonlinear static and dynamic analysis was conducted. The author had found that the results from the analyses were smaller than the ones according to ASME rules [45].

Pazand [47] simulated the mechanical behaviour of a direct fired rotary cement kiln. It was expected that maximum deformation occurs at the support points where the circular cross section becomes oval and between the supports where the shell deflects downwards. It was explained that most calculations of stresses and deformations were done by modelling the kiln as a static beam of annular cross section. Recently FEM was used to analyse kilns but none have taken into account the refractory lining. The shell material is considered to be isotropic, linear elastic, with temperature dependent characteristics. The passing material within the kiln was modelled as a distributed load. The mesh used in the analysis was comprised of 24 circumferential elements and 44 longitudinal. The model was able to expand longitudinally, deflect and rotate according to the boundary conditions. The author based the analysis on the Von-Mises failure criteria. It was discovered that the maximum stress occurs at and around the tires of a maximum value of 11.6 MPa and maximum deflection occurs between first and second supports with a magnitude of 7.89 mm. The results were validated experimentally. The errors between the simulation and experimental work was 0.077 for the maximum stress and 0.039 for the displacement.

Deshpande [48] developed an analysis on kiln tyre contact stress. The analyses presented the type of loads the tyres and rollers experience. The kiln was assumed to be simply supported. The type of loads include [48]:

1. Refractory loads: Kilns are divided into three different zones namely inlet, transition and burning zones. Different types of refractory lining is used in the three different zones
2. Point loads: These loads include the added equipment such as the girth gear, inlet seal and outlet seal.
3. Coating load: Due to the chemical reaction, material coating is formed on the inside of the kiln refractory.
4. Material filling load: The kiln is filled 5-10% in inlet and transition and 8-15% in the burning zone.
5. Self-weight: Is the load due to the weight of the kiln itself.

The mentioned loads were equally distributed loads on each roller pair. The contact stresses for the tyre and roller were modelled in Abaqus and only half of the tyre and roller were considered. The problem was modelled as a linear problem and the contact condition was modelled using contact pair approach. The contact property was assumed frictionless. When the results from the numerical model was compared to the analytical results, the maximum pressure in the FEM analyses achieved 344.4 MPa and from the analytical analyses of 431.9 MPa. The maximum shear stress from the model was 90.68 MPa and from the analytical results a maximum shear stress of 68.59 MPa was achieved [48].

Krishnan [49] achieved mechanical stability of rotary kilns by using finite element method. The purpose of the investigation was to determine the maximum stress values and locations in the rollers.
and shaft material. For the analysis, different positions of the bushings were used to achieve better stability. The most critical point of the shaft is where the shaft enters the raceway bushing. In the case where the bushings are parallel to the shaft, a maximum deflection of 0.2 mm and a maximum stress of 100 MPa was achieved. In the case where only the right bushing is not parallel to the shaft, a maximum deflection of 0.35 mm and a maximum stress of 150 MPa was obtained. Lastly, in the case where both bushings were not parallel to the shaft, a maximum deflection of 1.1 mm and a maximum stress of 210 MPa was calculated. From the analysis only perfect alignment of the roller shaft and the sleeve bearing is adequate for use in industry, which is when both bushings on each side are parallel to the shaft of the roller [49].

2.6 Concluding Remarks

Industry kilns were developed to be used for solid processing by heating, reacting and drying. Different types of kilns exist in industry for the different type of applications and process material characteristics. Directly fired rotary kilns undergo three different heat transfer mechanisms which are conduction, convection and radiation. Radiation is said to be to be the main mechanism of heat transfer. From literature it was found that the main concerns to take into account when modelling direct fired rotary kilns was ovalization, stresses and displacements experienced by the system. It is determined that the maximum deflection occurs between support points where the process material is loaded. Chapter 3.0 includes the experimental aims and experimental procedure in order to investigate the structural performance of a direct-fired rotary kiln pilot plant under different loads.
3.1 General Remarks

Chapter 2.0 presented the theoretical background of the origin and development of kilns. Theory included the different types of kilns, design of direct-fired rotary kilns and performance and numerical analysis associated with direct-fired rotary kilns, paying close attention to heat transfer and structural analysis using numerical modelling techniques. The following chapter outlines the equipment used in obtaining the experimental data and the procedure which was followed. The aims of the experiment, as well as the experimental variables, are presented from which an experimental matrix was developed.

3.2 Experimental Aims

The aims of the experiment were:

1. To measure the strain state of the outer shell of the direct-fired rotary kiln during rotation under its own weight.
2. To measure the strain state of the outer shell of the direct-fired rotary kiln during rotation under its own weight and the weight of the added platinum concentrate.
3. To measure the strain state of the outer shell of the direct-fired rotary kiln during rotation when a thermal load and added weight is applied.
4. Measure the temperature change of the process during start up and shut down.

3.3 Material Description

The strain measurements were recorded at a centre point between the two rider rings on the outer shell of the direct-fired rotary kiln. The outer shell of the kiln is made of S 355 JR. Table 3.1 and Table 3.2 present the composition and properties of S 355 JR respectively as given in the manufacturer certificate. The thickness of the kiln shell is ≤16 mm. On the other hand, Tables 3.3 and 3.4 present the material properties of the support rings, which in this case is EN8. Table 3.5 indicates the material properties of the individual refractory materials castable Verokast and fire brick respectively. Table 3.6 showed the mechanical properties relative to platinum concentrate which was used as the process material in the kiln. All material properties where gathered from manufactures certificates and handbooks and done at room temperature, unless specifically stated for the respective material property.

<table>
<thead>
<tr>
<th>Max C</th>
<th>Max Mn</th>
<th>Max Si</th>
<th>Max P</th>
<th>Max S</th>
<th>Max Cu</th>
<th>Max N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.24</td>
<td>1.6</td>
<td>0.55</td>
<td>0.035</td>
<td>0.035</td>
<td>0.55</td>
<td>0.012</td>
</tr>
</tbody>
</table>
Table 3.2: Mechanical Properties of the Kiln Shell Material S 355 JR at t≤16

<table>
<thead>
<tr>
<th>Yield (Min) (MPa)</th>
<th>Tensile (Min/Max) (MPa)</th>
<th>Poisson’s Ratio</th>
<th>Elastic Modulus (GPa)</th>
<th>Thermal Expansion (10⁻⁶/K)</th>
<th>Thermal Conductivity (W/m-K)</th>
<th>Specific Heat (J/kg.K)</th>
<th>Melting Temp (°C)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>355</td>
<td>470/630</td>
<td>0.3</td>
<td>210</td>
<td>10</td>
<td>25</td>
<td>460</td>
<td>1510</td>
<td>7850</td>
</tr>
</tbody>
</table>

Table 3.3: Chemical Composition of EN 8 in percentage

<table>
<thead>
<tr>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.44</td>
<td>0.40</td>
<td>1.00</td>
<td>0.05</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table 3.4: Material Properties of EN8

<table>
<thead>
<tr>
<th>Yield (Min) (MPa)</th>
<th>Tensile (Min/Max) (MPa)</th>
<th>Poisson’s Ratio</th>
<th>Elastic Modulus (GPa)</th>
<th>Thermal Expansion (10⁻⁶/K)</th>
<th>Thermal Conductivity (W/m-K)</th>
<th>Specific Heat (J/kg.K)</th>
<th>Melting Temp (°C)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>465</td>
<td>700/850</td>
<td>0.3</td>
<td>200</td>
<td>10</td>
<td>54@20°C</td>
<td>460</td>
<td>1510</td>
<td>7850</td>
</tr>
</tbody>
</table>

Table 3.5: Refractory Technical Specifications

<table>
<thead>
<tr>
<th>Material</th>
<th>Elastic Modulus (GPa)</th>
<th>Thermal Conductivity (W/m-K)</th>
<th>Specific Heat (J/kg.K)</th>
<th>Max Service Temperature (°C)</th>
<th>Bulk Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Insulating Brick: V24</td>
<td>3.69</td>
<td>0.4 (@ 600°C)</td>
<td>110</td>
<td>1400</td>
<td>1100</td>
</tr>
<tr>
<td>Conventional Castables Verokast 1500</td>
<td>13.2</td>
<td>1.0 (@ 1000°C)</td>
<td>105</td>
<td>1500</td>
<td>2270</td>
</tr>
</tbody>
</table>

Table 3.6: Thermal Properties of Platinum Concentrate

<table>
<thead>
<tr>
<th>Density (kg/m³)</th>
<th>Melting Point (°C)</th>
<th>Boiling Point (°C)</th>
<th>Specific Heat (J/kg.K)</th>
<th>Thermal Conductivity (W/m-K)</th>
<th>Coefficient of Thermal Expansion (10⁻⁶/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21450</td>
<td>1769</td>
<td>3825</td>
<td>126</td>
<td>69.1</td>
<td>9.10</td>
</tr>
</tbody>
</table>

3.4 Apparatus

The experimental results are dependent on the equipment used and, therefore, knowledge about each component is required in order to successfully obtain the correct experimental data. The list below indicates which equipment was used to obtain the experimental data, followed by a brief description of each important component. The experiment required the following equipment to gather the experimental data:

1. Drytech direct-fired rotary kiln pilot plant
2. WSDA®-Base-101 analog output base station
3. SG-Link®-LXRS wireless node
4. Strain gauge rosette
5. HUATO S220-T8 Temperature Data Logger
6. K-type Thermocouples
CHAPTER 3.0: EXPERIMENTAL PROCEDURE

7. Multi-meter
8. Scale
9. Measuring tape
10. Dry platinum concentrate

3.4.1 Overview of the Direct Heated Rotary Kiln Developed by Drytech

The direct-fired rotary kiln pilot plant at Drytech is a pilot plant used to illustrate its working principle to customers in order to get contracts for much larger scale direct-fired rotary kilns. The direct fired rotary kiln is positioned onto four trunnions. The trunnions are mounted on a mild steel skid. The direct fired rotary kiln pilot plant is small compared to commercial kilns found in industry. The rotary kiln’s overall dimensions are 1,334 mm OD x 2,963 mm Long, with a total heated length of 1,976 mm and a maximum inner diameter inside of the refractories of 500 mm.

The drive on the pilot plant incorporates the chain and sprocket drive arrangement. The directly fired rotary kiln is driven by an electrical motor which drives a small sprocket/pinion. The small pinion is directly coupled to the motor which drives the chain which then drives the larger sprocket. The large sprocket is welded onto the kiln outer shell. The drive arrangement is shown in Figure 3.1. A tensioner sprocket is used to maintain the required chain tension. The large sprocket is near the kiln end where the burner is situated.

![Figure 3.1: Sprocket and Chain Arrangement on Drytech’s Direct Fired Rotary Kiln Pilot Plant](image-url)

The direct-fired rotary kiln pilot plant is supported by two rider rings, which is supported by four trunnions. The rider rings are concentric to the kiln outer shell. The rider rings are supported by steel blocks, or chairs, which are welded to the kiln outer shell. The kiln is supported onto the mild steel skid by the use of two types of rollers. The one pair of rollers are two support rollers located near the burner. These rollers prevent axial movement of the kiln. The support roller also minimises slip of the rider ring and also acts as the thrust roller as on commercial kilns. On the discharge end of the kiln are two free rollers which allow axial movement of the kiln to accommodate actual thermal expansion.
and contraction. The way in which the rider rings are mounted to the kiln, and how the rider rings are supported by the rollers are shown in Figure 3.2.

To get the desired heat for the chemical process, an Eclipse TJ 040 burner is used in the direct-fired rotary kiln pilot plant. The burner is fired with propane supplied from gas bottles through a gas supply line as shown in Figure 3.3. The combustion air is supplied to the burner using an updraft fan. A control valve and a butterfly valve are used to control the amount of air and gas passed to the burner, thus providing a means to control the air to fuel ratio. Normal ceramic spark plugs are used to ignite the gas-air mixture to provide the flame inside the kiln. The combustion gases pass through the kiln length and exist through a converging nozzle on the other end of the kiln. The combustion gases, with entrained material, are pushed out into a cyclone and baghouse arrangement for off gas treatment to ensure safe emissions of the gas. Figure 3.4 shows a closer view of the burner arrangement.
3.4.2 SG-Link Equipment

Strain measurements were captured using a MicroStrain SG Link. This is a wireless strain transmission system which allows the strain logging node to be mounted onto the rotating shell, which transmits the strain data wirelessly to a data logging computer through a base station. The setup is controlled through Node Commander® Software [62].

3.4.2.1 Node

The SG-Link®-LXRS wireless nodes operate within a fast, synchronised, scalable network of wireless sensor nodes which could be located as far as 2 km in the line of sight of the WSDA®-Base. The nodes include an internal rechargeable Li-ion battery and is able to measure strain, torque, load, pressure and magnetic fields through a connector to user-supplied bridge sensor [63].

The features and benefits of the LXRS wireless node is that it supports hundreds of simultaneous sampling wireless nodes, node to node synchronisation of ±32 microseconds, ultra-stable on board precision timing reference of ±3 ppm over industrial temperature range and programmable communication range from 70m to 2km [63].

The SG-Link®-LXRS wireless node is able to do sampling for three different modes, namely continuous sampling at one sample per hour to 512 Hz; periodic burst sampling from 32 Hz to 4,096 Hz and; data logging from 32 Hz to 4,096 Hz [63].
CHAPTER 3.0: EXPERIMENTAL PROCEDURE

The nodes may be applied to wireless flight testing of aircrafts, condition based monitoring of machines, health monitoring of structures and vehicles, smart structures and materials, robotics and machine automation, experimental test and measurements, vibration and acoustic noise testing, sports performance and sports medicine analysis and distributed security networks [63]. Figure 3.5 illustrates a SG-Link®-LXRS wireless node. The experimental data for the strain readings were acquired using a quarter bridge configuration. The wiring for the quarter bridge is given in Figure 3.6.

Figure 3.5: SG-Link®-LXRS Wireless Nodes [63]

Figure 3.6: Wiring of a SG-Link®-LXRS Wireless Node for Quarter Bridge Configuration [64]

3.4.2.2 Base Station

The WSDA®-Base-101 analog output base station operates as an essential part of MicroStrain®LXRS™ wireless sensor networks. It provides communication between a host PC (personal computer), single board computer and remote wireless nodes. Together with Node Commander® software, the base station supports the configuration of the wireless nodes including discovery, initialising, radio frequency, sample rate, calibration and managing node batteries which include sleep, wake and cycle power [65].
The base station supports all data acquisition sessions between the wireless nodes and host computers. The supported node sampling modes includes synchronised sampling, low duty cycle sampling, continuous sampling, periodic burst sampling, event triggered sampling and data logging [65]. The benefits and features of the base station is that it is able to support hundreds of simultaneously sampling wireless sensor nodes, node to node synchronisation of +/- 32 microseconds, extended wireless communication range of 2km and eight channel support for data acquisition equipment. The base station may be used for monitoring machines and aircrafts, health monitoring of civil structures and vehicles, smart structures and materials, experimental tests and measurements, robotics and machine automation, vibration and acoustic noise testing, sports performance and sports medicine analysis and distributed security networks [65]. Figure 3.7 illustrates a WSDA®-Base-101 analog output base station.

3.4.3 Strain Gauge Rosette

Strain gauges are electrical sensors that measure strain of a material by having an electrical resistance change when an applied load stretches or compresses the material under investigation. Strain gauges are small sheets of metal foil cut into a zig-zag patterns. Strain gauges capture negative and positive data. The negative data indicates compression and positive data indicate a tensile strain [66]. Figure 3.8 illustrates a typical strain gauge.
The strain gauge rosette consists of two or more co-located singular strain gauges orientated at fixed angles with respect to one another. There are two different ways in which rosette strain gauges may be offered. One of which is the stacked rosette for strict co-location, where the individual gauges are mounted on top of one another. The more common possibility is where the gauges are placed in a tightly packed pattern as close as possible to the rosette centre. Rosettes typically involve two to four strain gauges with relative orientations of 30°, 45°, 60° or 90°. At least three independent strain readings are required to define the two dimensional state of strain if no other information is available. Therefore, the three gauge rosettes are the most popular [68].

The strain gauge used for the experimental investigation was UFRA-3-350-11. Table 3.7 shows the symbol designation of the strain gauge rosette. This gauge was selected because the thermal coefficient of expansion matches that of the rotary kiln’s shell material. This implies that there is no need for temperature compensation during testing.

Table 3.7: Strain Gauge Configuration [69]

<table>
<thead>
<tr>
<th>Gauge Series</th>
<th>Grid Pattern</th>
<th>Active grid Length (mm)</th>
<th>Gauge resistance (Ω)</th>
<th>Thermal Compensation (ppm/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UF</td>
<td>RA</td>
<td>3</td>
<td>350</td>
<td>11</td>
</tr>
</tbody>
</table>

Where UF is the foil material temperature range, in this case -20 to 150 °C and; RA is the type of strain gauge rosette, which in this case is a square rosette strain gauge where the three individual strain gauges are orientated at 45° with respect to one another.

The technical specifications of the UFRA-3-350-11 rosette, according to the manufacture data sheet, is given in Table 3.8:

Table 3.8: Technical Specifications of UFRA-1-350 [70]

<table>
<thead>
<tr>
<th>Gauge Pattern</th>
<th>Type</th>
<th>Gauge Length (mm)</th>
<th>Gauge Width (mm)</th>
<th>Backing Diameter (mm)</th>
<th>Coefficient of Thermal Expansion (x10^{-6}/°C)</th>
<th>Resistance (Ω)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UFRA-1-350</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UFRA-3-350-11</td>
<td></td>
<td>3</td>
<td>2</td>
<td>Ø10.0</td>
<td>11.8</td>
<td>350</td>
</tr>
<tr>
<td>UFRA-3-350-17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UFRA-3-350-23</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.4.4 Temperature Data Logger

The S220 8-channel thermocouple thermometer is a data logger which accurately measures temperature using different types of thermocouples such as K, J, E, T, R, S, N and B-type thermocouples. The data logger is able to measure in °C and °F. Other features of the data logger include a wide verity of interchangeable thermocouple probes, LCD (liquid crystal display) display with backlight, max hold and data hold, mini USB (universal serial bus) interface and is able to record 36,000
log readings [71]. The technical specifications of the data logger are given in Table 3.9. Figure 3.9 presents a HUATO S220 8-channel thermocouple temperature data logger used in this study.

Table 3.9: Specifications of the S220 Thermocouple Thermometer [71]

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measuring Accuracy</td>
<td>+/- 0.2% FS</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.1°C</td>
</tr>
<tr>
<td>Sampling Rate</td>
<td>Fastest 1/sec; from 1 to 240 seconds can be set</td>
</tr>
<tr>
<td>Power Supply</td>
<td>3.6V Lithium Battery</td>
</tr>
<tr>
<td>Display</td>
<td>LCD Display</td>
</tr>
<tr>
<td>Product Dimensions</td>
<td>158 x 95 x 35 mm</td>
</tr>
<tr>
<td>LCD Size</td>
<td>65 x 53 mm</td>
</tr>
<tr>
<td>Net Weight</td>
<td>320 g</td>
</tr>
</tbody>
</table>

Figure 3.9: HUATO S220-T8 Temperature Data Logger [71]

3.4.5 K-Type Thermocouple

Thermocouples are sensors, which are used to measure temperature. Thermocouples are made of two wire legs made from different metals. The wire legs are welded together at one end which creates a junction. At the junction, temperature is measured. As the junction experiences a change in temperature, a voltage is created. The voltage can then be interpreted using thermocouple reference tables to calculate the temperature [72].

Thermocouples are used in different scientific and industrial applications. They may be found in almost every industrial market such as power generation, oil/gas, pharmaceutical, biotech, cement, paper and pulp. Thermocouples may even be found in everyday appliances such as stove furnaces and toasters. Thermocouples are widely used due to their low cost, high temperature limits, wide temperature ranges and durable nature. It is important to note that thermocouples are usually enclosed in a protective sheath to isolate it from the local atmosphere. The sheath reduces the effects of corrosion [72].

There are different types of thermocouples to choose from. Each thermocouple group has its own unique characteristics in terms of temperature range, durability, vibration, resistance, chemical
resistance and application compatibility. The J, K, T, and E type thermocouples are base metal thermocouples and are the most common types. The R, S, and B-type thermocouples are noble metal thermocouples and are used in high temperature applications [72]. For the following study, the K-Type thermocouple was used throughout the study since the thermocouple’s temperature range is sufficient for the experimental work.

K-type thermocouples, either Nickel-Chromium or Nickel-Alumel, is the most common type of thermocouple. The thermocouple is inexpensive, accurate, reliable and has a wide temperature range. The temperature range for the grade wire is -270 to 1260 °C, extension wire from 0 to 200 °C. The accuracy of the thermocouple is the greater of the standard from ± 2.2 °C or ± 0.75 % and special limits of error either ±1.1 °C or 0.4 % [72].

3.5 Experimental Procedure and Set-up

The following list of steps were used in determining the outer and inner temperatures of the directly fired rotary kiln pilot plant in operation. The experimental work was conducted in winter in the month of June in order to investigate the worst case scenario. Due to the operation of the kiln, there is a need to measure the temperatures on the outer shell of the kiln and inner surface of the refractory lining since temperature plays an important role in the structural behaviour of the direct-fired rotary kiln. Strain measurements were done for the three different scenarios namely the strain experienced due to rotation, loading and heating. The steps are as follows:

1. To ensure accurate readings, all apparatus were charged before use. The apparatuses that had to be charged included the SG-Link®-LXRS wireless nodes and the S220 thermocouple temperature data logger. If the mentioned apparatuses were not charged, recordings could stop at any moment during testing. If this occurred then time would be wasted and new data would need to be obtained.

2. Prior to the day of testing, Mr. Dewald Scholtz (engineer at Drytech International) installed the K-Type thermocouples. A total of nine thermocouples were installed. All the thermocouples in the experimental work were K-type thermocouples. Four were placed on the outer shell and four were placed on the inner refractory lining. The inner thermocouples were 50 mm from the inside surface of the refractory and were insulated with Den Braven high temperature sealant. The purpose of the sealant was to prevent direct contact between the thermocouples and the flame from the burner and the platinum concentrate. An additional thermocouple was placed right through the kiln into the inner refractory lining, allowing it to measure the inner temperature of the directly fired rotary kiln at the exit end of the kiln. The mentioned thermocouple was placed furthest away from the flame so that the thermocouple would not get damaged due to the burner flame. The inner thermocouples are shown in Figure 3.10. The outer and inner thermocouples were equi-spaced, 400 mm apart from each other. The placement of all nine thermocouples, along the length of the directly fired rotary kiln shell, is shown in Figure 3.11.
3. It was expected, based on literature [47], that the maximum deflection that the directly fired rotary kiln will experience would be in the centre, which lies between the two rider rings. In order to place the strain gauges at the centre of the kiln shell, two lines were drawn on the outer shell. The one line was drawn from the support block of one of the rider rings to the opposite rider ring support block. A second line was drawn in the same manner, but one support block down. Each line was then marked off in the centre and then a straight line was drawn from centre to centre. To ensure accurate data, the strain gauges had to be applied as accurately as possible.

4. The steps that are required to bond the strain gauge rosette to the shell of the pilot plant kiln, according to [73], are as follows:
   4.1 Select adhesive: Must be suitable for the test conditions i.e. an adhesive which may be used at temperatures from 20 °C to 100 °C.
   4.2 Surface treatment: Remove any grease, rust, paint etc. from the bonding surface of the pilot plant shell. The surface of the kiln shell was buffered with an industrial grinder and then lightly polished with an adhesive paper, and wiped down with acetone to ensure the bonding surface is clean. The prepared surface is shown in Figure 3.12.
4.3 Marking strain gauge position: After the surface was cleaned, the lines were redrawn on the shell. A sharp knife was then used to trace the lines on the shell, and the red marker lines were cleaned off so that the ink would not have an effect on the strain gauge data measurements.

4.4 Gauge installation: The adhesive was applied to the surface of the kiln shell and on the backing of the strain gauge rosette. The strain gauge rosette was then placed on the kiln shell at the marked position by not applying to much force, but ensuring all the edges of the backing is stuck on well. The strain gauge rosette was bonded to the shell allowing the axial strain gauge, at 0°, to be in line with the horizontal line marked on the shell. The adhesive was allowed to cure for 24 hours. The bonded strain gauge rosette to the shell is shown in Figure 3.13.
4.5 Gauge installation check: The strain gauge resistance was then checked with the use of an ohm meter. The ohm meter had to read 350 Ω to ensure that the strain gauge was not damaged during installation.

4.6 Lead wire attachment: Lead wires were soldered to the strain gauge rosette through the connecting terminals. An epoxy resin was applied to secure the terminal wires from the strain gauge so that they would not be disconnected accidentally. Care was taken when applying the epoxy so that the epoxy would not touch the strain gauge wire, which could have had an effect on the strain readings. The ohm reading was then taken again to ensure that the strain gauge rosette was not damaged from the epoxy and to make sure that the terminal wires were making a proper connection with the strain gauge rosette. The secured strain gauge rosette is shown in Figure 3.14.
5. The kiln was allowed to rotate till the strain gauge was positioned on the horizontal plane. In order to achieve the horizontal plane, a mark was drawn from one of the stationary bolts, bolting the burner to the back of the direct-fired rotary kiln. Once the horizontal line was drawn on the outer shell, marked by the knife, matched up with the horizontal line from the burner, the kiln was stopped. The purpose of this was to ensure that calibration of the nodes to the PC were done at the neutral axis when the stress is expected to be zero.

6. Connecting wires were inserted to the SG-Link®-LXRS wireless nodes using the wiring schematic for a quarter bridge as shown in Figure 3.6. The base of the SG-Link®-LXRS wireless nodes were stuck down onto the kiln shell using double-sided tape. To complete the circuit between the strain gauge and the nodes, the connecting wires from the nodes were soldered to the strain gauge rosette connecting terminals. Each node recorded the strain from one of the strain gauges on the rosette. Once the wires were soldered to the strain gauges, masking tape was used to stick down the connecting wires to avoid the wires catching onto something during rotation and then being disconnected. The nodes were then calibrated before loading, rotation or heat using strain wizard on the software “Node Commander”. The configuration of the nodes are shown is Figure 3.15.

7. The complete configuration of the installed thermocouples and nodes are shown in Figure 3.16.
8. Once the nodes were calibrated, experimental data begun before loading. The direct fired rotary kiln was allowed to rotate at 0.74 RPM for 57 minutes and 17 seconds. As the direct fired rotary kiln rotated, a digital scale was used to measure the amount of dry platinum concentrate which would be processed in the directly fired rotary kiln pilot plant. The kiln was then stopped and disassembled. The platinum concentrate was then loaded and the kiln was reassembled. The strain readings were then taken for 33 minutes and 11 seconds due to time limitations at the laboratory facility. The digital scale is shown in Figure 3.17. The loaded platinum concentrate is shown in Figure 3.18.

9. Once the platinum concentrate was loaded, the final assembly was done on the kiln. The final assembly is shown in Figure 3.19.
10. Before the directly fired kiln could be switched on, final checks were done to make sure everything was in working order and was safe. Two separate S220 temperature data loggers were connected and paired with their respective thermocouple terminals. One S220 temperature data logger was used to record the temperatures from the thermocouples placed along the length of the kiln on the outer shell surface and the inner surface of the refractory lining. The second S220 temperature logger was used to measure the temperature of the additional thermocouple. The kiln was switched on to rotate and the air flow and gas flow were adjusted using the control valves and butterfly valves found on the airline and gas line. The control panel, on the skid frame, was used to control the rotation of the direct-fired rotary kiln pilot plant. Once the desired speed was achieved, a signal from the control panel was sent to the burner to ignite the flame. Small adjustments were made to the air flow and gas flow to achieve a steady state temperature from the burner. Temperature readings using the S220 temperature data logger begun once the rotary kiln began to rotate. The kiln was allowed to heat up for 3 hours 39 minutes and 21 seconds.

3.6 Experimental Matrix

3.6.1 Independent Variables

Independent variables in an experimental matrix are variables that are able to change during the experiment and have a direct influence on the experiment. The independent variables for the following experiment include:

1. Kiln shell material
2. Mass of the platinum concentrate
3. Rotational speed
4. Fuel type
5. Air to fuel ratio
6. Ambient conditions
7. Time
3.6.2 Dependent Variables

Dependent variables in an experimental matrix are variables that change during the experiment depending on the state of the system and how the independent variables are utilised. The dependent variables are the variables which are investigated and determined. The dependent variables for the following experiment include:

1. Kiln operational temperatures
2. Induced strain
3. Induced stress

3.6.3 Constant Variables

The constant variables within an experimental matrix are the variables that remain constant for the duration of the experimental work. The constant variables include:

1. Material of the kiln shell
2. Process material
3. Mass of the process material
4. Rotational speed
5. Type of fuel
6. Air flow
7. Fuel flow
8. Fuel to air ratio
9. Ambient conditions

3.6.4 Experimental Matrix

Table 3.10 is the expected experimental matrix in terms of the dependent and independent variables.
Table 3.10: Preliminary Experimental Matrix

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Temperature at Various Points along the Length of the Direct Fired Rotary Kiln (°C)</th>
<th>Experimental Strain (µmm/mm)</th>
<th>Principal Strains (µmm/mm)</th>
<th>Principal Stress (Pa)</th>
<th>Orientation of the principal Stresses (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Position 1</td>
<td>Position 2</td>
<td>Position 3</td>
<td>Position 4</td>
<td>ε₀°</td>
</tr>
<tr>
<td>1</td>
<td>11</td>
<td>12</td>
<td>13</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>21</td>
<td>22</td>
<td>23</td>
<td>24</td>
<td>25</td>
</tr>
<tr>
<td>3</td>
<td>31</td>
<td>32</td>
<td>33</td>
<td>34</td>
<td>35</td>
</tr>
<tr>
<td>4</td>
<td>41</td>
<td>42</td>
<td>43</td>
<td>44</td>
<td>45</td>
</tr>
<tr>
<td>5</td>
<td>51</td>
<td>52</td>
<td>53</td>
<td>54</td>
<td>55</td>
</tr>
<tr>
<td>6</td>
<td>61</td>
<td>62</td>
<td>63</td>
<td>64</td>
<td>65</td>
</tr>
</tbody>
</table>
3.7 Concluding Remarks

Chapter 3.0 presented the experimental aims, which were needed to be addressed during the experiment. The chapter also described the materials, apparatus and procedure followed in measuring the structural response, to different load cases, of the direct-fired rotary kiln. The various independent and dependent variables of the experimental investigation were identified, from which the experimental matrix was developed and presented. Chapter 4.0 will present the results obtained from the experimental measurements, as well as the principal stresses calculated from the measured experimental strains.
CHAPTER 4.0: EXPERIMENTAL RESULTS

4.1 General Remarks

Chapter 3.0 described in detail how the structural response of the kiln, under different loads was experimentally measured. This chapter presents the results of the experimental tests conducted for varying loading conditions. The measured strains were converted into stresses using the stress-strain relationships. The experimental results will be used to validate the numerical model that was developed to study the structural response of the pilot direct fired rotary kiln plant.

4.2 Relevant Stress Theory

4.2.1 Strain Transformation

The experimental values obtained from a strain gauge rosette may be transformed to determine the full strain field in the measurement plane. The plane strains associated with the three strain readings gathered from a strain gauge rosette may be calculated using the transformation equation 4.1 [74]:

$$\varepsilon_\theta = \frac{\varepsilon_x + \varepsilon_y}{2} + \left(\frac{\varepsilon_x - \varepsilon_y}{2}\right) \cos 2\theta + \frac{\gamma_{xy}}{2} \sin 2\theta$$  

Where $\varepsilon_\theta$ is the experimentally measured strain in $\mu$mm/mm; $\varepsilon_x$ is the transformed strain in the $x$ direction in $\mu$mm/mm; $\varepsilon_y$ is the transformed strain in the $y$ direction in $\mu$mm/mm; $\theta$ is the angle of the strain gauge placement in degrees and; $\gamma_{xy}$ the shear strain in the $x$-$y$ plane in $\mu$mm/mm [74].

Equation 4.1 may be applied three times for the values of $\theta$ of the specific strain gauge rosette. Most strain gauge rosettes are either rectangular with $\theta = 0^\circ, 45^\circ$ and $90^\circ$ or delta rosette strain gauges with $\theta = 0^\circ, 60^\circ$ and $120^\circ$. For both cases, the calculations are simplified if the $x$-axis is chosen as the reference axis at $\theta = 0^\circ$. Equation 4.1 at $\theta = 0^\circ$ reduces to [74]:

$$\varepsilon_0 = \frac{\varepsilon_x + \varepsilon_y}{2} = \varepsilon_x$$  

When $\theta = 45^\circ$ equation 4.1 simplifies to [74]:

$$\varepsilon_{45} = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{\gamma_{xy}}{2}$$

$$\gamma_{xy} = 2\left(\varepsilon_{45} - \frac{\varepsilon_x + \varepsilon_y}{2}\right)$$

Similarly, when $\theta = 90^\circ$ equation 4.1 simplifies to [74]:

$$\varepsilon_{90} = \frac{\varepsilon_x + \varepsilon_y}{2} + \frac{-\varepsilon_x + \varepsilon_y}{2} = \varepsilon_y$$
4.2.2 Principal Strains

The calculated transformed strains, from equations 4.2 to 4.4, are used to calculate the principal strains at a specific point on the material. The equation for principal strains is determined by the following equation [74]:

\[ \varepsilon_1, \varepsilon_2 = \frac{\varepsilon_x + \varepsilon_y}{2} \pm \frac{1}{2} \sqrt{\left(\varepsilon_x - \varepsilon_y\right)^2 + 4\gamma_{xy}^2} \]  

where \( \varepsilon_1 \) is the maximum principal strain in \( \mu \text{mm/mm} \); \( \varepsilon_2 \) is the minimum principal strain in \( \mu \text{mm/mm} \) and; \( \varepsilon_x, \varepsilon_y \) and \( \gamma_{xy} \) are the transformed strains calculated from the strain gauge rosette strain measurements. The two principal strains occur on mutually perpendicular planes termed the principal plane [74]. The direction of the principal strain axes is given by equation 4.6 [74]:

\[ \tan 2\theta_p = \frac{\gamma_{xy}}{\varepsilon_x - \varepsilon_y} \]  

Where \( \theta_p \) is the direction of the maximum principal strain in degrees \( (\degree) \). The direction of the minimum principal strain maybe calculated by the following [74]:

\[ \theta_q = 90^\circ + \theta_p \]  

Where \( \theta_q \) is the direction of the minimum principal strain in degrees \( (\degree) \) [74].

4.2.3 Principal Stresses

By applying the stress-strain relationships and noting that in practical situations the stress component in the z-direction is assumed to be zero, the principal stresses may be calculated from the principal strains [75]. By using equation 4.8 and 4.9, the principal stresses in the plane of measurement may be calculated by applying Hooke’s law and are given mathematically by the following [75]:

\[ \sigma_1 = \frac{E}{1-\nu^2}(\varepsilon_1 + \nu\varepsilon_2) \]  

\[ \sigma_2 = \frac{E}{1-\nu^2}(\varepsilon_2 + \nu\varepsilon_1) \]  

where \( \sigma_1 \) is the maximum principal stress in MPa; \( \sigma_2 \) is the minimum principal stress in MPa; \( \varepsilon_1 \) and \( \varepsilon_2 \) are the principal strains in the plane of measurement in \( \mu \text{mm/mm} \) and; \( \nu \) is the Poisson’s ratio of the material which is dimensionless [75].

4.3 Results

The results from the experimental data is presented in the following sub-sections. The discussion of the experimental results are followed after the results are presented. The discussion will explaining each load case separately by referring to the respective graphs obtained from the experimental results.
4.3.1 Node Orientation on the Direct Fired Rotary Kiln Shell

Three quarter bridge nodes were used to measure the strain experienced by the shell of the direct-fired rotary kiln at a selected point on the surface of the kiln shell for the three different load cases, namely (1) rotation, (2) rotation and loading and (3) rotation, loading and heating. Figure 4.1 illustrates which node number measures which strain direction. The strain directions in question include longitudinal, circumferential and lateral at 45°. The node numbers for each node was programmed into the node beforehand and were given as default.

![Figure 4.1: Schematic of Node Orientation](image)

4.3.2 Principal Stress Calculations

The numerical procedure that will be followed to calculate the principal stresses at a point on the outer shell of the kiln from the experimental strain will use equations 4.1 through to 4.9. Equation 4.1 will be used to transform the measured strain readings to plane strains. Equation 4.5 will be used to calculate the principal strains at the point of measurement and equations 4.6 and 4.7 will be used to calculate the direction of the principal plane. Equation 4.8 will be used to determine principal stresses that the kiln experienced at the measurement point for each load case. The way each reading was analysed and used for computation is demonstrated below by taking the very first reading in the load case for rotation:

At 0°:

\[
\varepsilon_0 = -0.000115722 = \frac{\varepsilon_{11}}{2} + \frac{\varepsilon_{22}}{2} + \left(\frac{\varepsilon_{11}}{2} - \frac{\varepsilon_{22}}{2}\right) \cos(2(0)) + \frac{\gamma_{12}}{2} \sin(2(0))
\]

\[
= \frac{\varepsilon_{11}}{2} + \frac{\varepsilon_{22}}{2} + \frac{\varepsilon_{11}}{2} - \frac{\varepsilon_{22}}{2}
\]
\[ \varepsilon_x = -0.000115722 \mu \text{mm/mm} \]

At 45°:

\[ \varepsilon_{45} = \frac{\varepsilon_{11}}{2} + \frac{\varepsilon_{22}}{2} + \left( \frac{\varepsilon_{11}}{2} - \frac{\varepsilon_{22}}{2} \right) \cos(2(45)) + \frac{\gamma_{12}}{2} \sin(2(45)) \]

\[ = \frac{\varepsilon_{11}}{2} + \frac{\varepsilon_{22}}{2} + \frac{\gamma_{12}}{2} \]

\[ \gamma_{xy} = 2 \left( \varepsilon_{45} - \frac{\varepsilon_{11}}{2} - \frac{\varepsilon_{22}}{2} \right) \]

At 90°:

\[ \varepsilon_{90} = \frac{\varepsilon_{11}}{2} + \frac{\varepsilon_{22}}{2} + \left( \frac{\varepsilon_{11}}{2} - \frac{\varepsilon_{22}}{2} \right) \cos(2(90)) + \frac{\gamma_{12}}{2} \sin(2(90)) \]

\[ = \frac{\varepsilon_{11}}{2} + \frac{\varepsilon_{22}}{2} - \frac{\varepsilon_{11}}{2} + \frac{\varepsilon_{22}}{2} \]

\[ \varepsilon_y = 32.8789 \mu \text{mm/mm} \]

Therefore, the plane shear strain is:

\[ \gamma_{xy} = 2 \left( 42.3276 - \frac{0.000115722}{2} - \frac{32.8789}{2} \right) \]

\[ \gamma_{xy} = 51.7764 \mu \text{mm/mm} \]

Therefore, by using the transformed plane strains the principal strains may be determined by:

\[ \varepsilon_1 = \frac{-0.0001157 + 32.88}{2} + \frac{1}{2} \sqrt{(-0.0001157 - 32.88)^2 + (51.78)^2} \]

\[ = 47.11 \mu \text{mm/mm} \]

\[ \varepsilon_2 = \frac{-0.0001157 + 32.88}{2} - \frac{1}{2} \sqrt{(-0.0001157 - 32.88)^2 + (51.78)^2} \]

\[ = -14.23 \mu \text{mm/mm} \]

The orientation of the maximum principal strain may be determined by:

\[ \tan 2\theta_p = \frac{51.78}{-0.0001157 - 32.88} \]

\[ \theta_p = -28.79^\circ \]

And the minimum principal strain direction may be determined as:

\[ \theta_q = -28.79^\circ + 90^\circ \]

\[ \theta_q = 61.21^\circ \]

Therefore, the maximum and minimum principal stresses may be calculated by the following:

\[ \sigma_1 = \left( \frac{200 \text{ GPa}}{1 - 0.2\varepsilon} \right) (47.11\mu + 0.3(-14.23\mu)) \]

\[ \sigma_1 = 9.41 \text{ MPa} \]
\[ \sigma_2 = \left( \frac{200 \text{GPa}}{1 - 0.2^2} \right) \left( (-14.23 \mu) + 0.3(47.11 \mu) \right) \]

\[ \sigma_2 = -21.0 \text{ kPa} \]

The orientation of the principal plane is shown in Figure 4.2.

The same procedure was used to evaluate the other results for each point of measurement for all three load cases.

4.3.3 Strain Measurement Due to Rotation

The procedure to measure the strain was explained in Chapter 3.0. The nodes were supplied pre-calibrated by the manufacturer. The nodes were then zeroed at the neutral axis, or in other words when the nodes were aligned perfectly horizontal to a reference point. The reference point was the position shown in Figure 4.3. The reference point was chosen on the burner bolt since it remains stationary as the kiln rotates.
CHAPTER 4.0: EXPERIMENTAL RESULTS

The strain data was gathered for 3,437 seconds or 57 minutes and 17 seconds. The kiln was run 0.74 rpm and it took the kiln 81 seconds to complete one complete revolution. The principal stresses that were experienced by the kiln were calculated using Hooke’s law. Figure 4.4 shows the kiln shell’s strain response to self-weight and rotation in terms of the measured strain in the longitudinal direction (Node 918), the circumferential direction (Node 1072) and the lateral direction at 45° (Node 34457). The principal stresses of the kiln shell’s structural behaviour for the entire time history and for one revolution is shown in Figures 4.5 and 4.6 respectively. From the graphs, there is a clear indication that the strain in the lateral direction experiences the largest magnitude in terms of strain. The variations in the data illustrates that the kiln experienced tensile and compressive strains and stresses throughout the operation. The peaks in the readings are considered as tensile strains and the troughs in the readings are considered as compressive strains.
4.3.4 Strain Measurement Due to Rotation and Loading

The process material used for loading in this case was platinum concentrate. A total of 156.55 kg was loaded into the kiln which is greater than what the kiln at Drytech is usually loaded with. The kiln is usually filled up to 10% of its volume. The total time for the strain measurement was 33 minutes and 11 seconds. The time was limited for this load case due to the time constraint imposed by Drytech International Pty. Ltd. The rotational speed of the kiln was kept constant for all three tests. Figure 4.7 presents the measured strain for the direct-fired rotary kiln pilot plant in the longitudinal direction (Node 918), the circumferential direction (Node 1072) and in the lateral direction at 45° (Node 34457) to investigate the structural response due to rotation including self-weight and added weight of the process material. Figure 4.8 and 4.9 illustrate the calculated principal stress that the kiln experienced throughout the load case and for one rotation respectively. From Figure 4.7, the measured strain in...
the longitudinal direction experienced the greatest variations in compressive and tensile strains. The largest magnitude of strain is in the 45° direction.

Figure 4.7: Measured Strain vs Time due to Rotation and Loading

Figure 4.8: Principal Stress vs Time due to Rotation and Loading
4.3.5 Strain Measurement Due to Rotation, Loading and Heating

Figure 4.10 shows the placement of each individual thermocouple. The thermocouples were placed 400 mm apart. The odd numbered thermocouples i.e. 1, 3, 5 and 7 measured the inner surface temperature of the direct-fired rotary kiln. The inner thermocouples were placed 50 mm from the inner surface in order to prevent the thermocouples to be in direct contact with the flame, flue gas and also the process material. The even numbered thermocouples i.e. 2, 4, 6 and 8 measure the surface temperature of the direct-fired rotary kiln shell and was of great interest and importance for the analysis. Position 1 and 2 are the thermocouples placed closet to the burner, whereas thermocouple potions 7 and 8 are furthest away from the burner.

The direct-fired rotary kiln was allowed to heat up for 3 hours 39 minutes and 21 seconds. The experimental data gathering for this experiment was done on a separate day, which allowed the test to be run for a longer period of time. Figure 4.11 presents the temperature distribution on the inner
surface of the direct-fired rotary kiln. Figure 4.12 presents the temperature gradient on the outer shell of the kiln due to the flame, flue gas and process material temperature with respect to time.
Figure 4.13 presents the measured strain data in the longitudinal direction (Node 918), the circumferential direction (Node 1072) and the lateral direction at 45° (Node 34457) in response to rotation, self-weight, added load and heat. Figure 4.14 and 4.15 present the calculated principal stresses that the kiln shell experienced throughout the load case and for one rotation respectively. From Figure 4.13, the measured strain in the longitudinal direction experienced an increase in the compressive and tensile strains as the temperature increased rapidly. For Figure 4.15, one complete rotation was displayed to get an understanding of the structural behaviour of the kiln at the recorded peak temperature. From the figure, it seemed that the kiln’s structural performance, in terms of principal stress, reached a steady state.
The results were furthered analysed in tabular form by investigating 9 different points throughout each individual load case. For each load case, three readings will be taken from the start of the recorded data, three in the middle and three near the end of the process. Table 4.1 to 4.3 present the structural behaviour, in terms of measured strain, transformed strain, principal strain and principal stresses. The experimental data that will be used in validating the numerical model is shown in Table 4.4. The data was gathered by calculating the average maximum and minimum principal stresses for each individual load case.
### Table 4.1: Experimental Results due to Rotation

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Temperature at Various Points along the Length of the Direct Fired Rotary Kiln (°C)</th>
<th>Experimental Strain (µm/mm)</th>
<th>Transformed Strain (µm/mm)</th>
<th>Principal Strains (µm/mm)</th>
<th>Principal Stresses (MPa)</th>
<th>Orientation of the principal Strains (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Position 1 20 20 20 20</td>
<td>$\varepsilon_{\theta}$</td>
<td>$\varepsilon_{45^\circ}$</td>
<td>$\varepsilon_{90^\circ}$</td>
<td>$\varepsilon_x$</td>
<td>$\varepsilon_y$</td>
</tr>
<tr>
<td>1</td>
<td>20 20 20 20</td>
<td>-1.16E-4</td>
<td>42.33</td>
<td>32.88</td>
<td>-1.16E-4</td>
<td>32.88</td>
</tr>
<tr>
<td>2</td>
<td>20 20 20 20</td>
<td>0.00</td>
<td>35.82</td>
<td>29.59</td>
<td>-3.24</td>
<td>29.59</td>
</tr>
<tr>
<td>3</td>
<td>20 20 20 20</td>
<td>0.00</td>
<td>32.56</td>
<td>26.00</td>
<td>-1.39</td>
<td>26.30</td>
</tr>
<tr>
<td>1146</td>
<td>20 20 20 20</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1147</td>
<td>20 20 20 20</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>1148</td>
<td>20 20 20 20</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>3436</td>
<td>20 20 20 20</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>3437</td>
<td>20 20 20 20</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>3438</td>
<td>20 20 20 20</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>
### Table 4.2: Experimental Results Due to Rotation and Loading

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Temperature at Various Points along the Length of the Direct Fired Rotary Kiln (°C)</th>
<th>Experimental Strain (µm/mm)</th>
<th>Transformed Strain (µm/mm)</th>
<th>Principal Strains (µm/mm)</th>
<th>Principal Stresses (MPa)</th>
<th>Orientation of the principal Strains (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Position 1 20 20 20 20</td>
<td>$\varepsilon_0^o$</td>
<td>$\varepsilon_{45}^0$</td>
<td>$\varepsilon_{90}^o$</td>
<td>$\varepsilon_x$</td>
<td>$\varepsilon_y$</td>
</tr>
<tr>
<td>1</td>
<td>20 20 20 20</td>
<td>54.20</td>
<td>117.21</td>
<td>72.33</td>
<td>54.20</td>
<td>72.33</td>
</tr>
<tr>
<td>2</td>
<td>20 20 20 20</td>
<td>58.36</td>
<td>100.93</td>
<td>69.05</td>
<td>58.36</td>
<td>69.05</td>
</tr>
<tr>
<td>3</td>
<td>20 20 20 20</td>
<td>56.51</td>
<td>100.93</td>
<td>72.33</td>
<td>56.51</td>
<td>72.33</td>
</tr>
<tr>
<td>664</td>
<td>20 20 20 20</td>
<td>61.61</td>
<td>110.70</td>
<td>78.91</td>
<td>61.61</td>
<td>78.91</td>
</tr>
<tr>
<td>665</td>
<td>20 20 20 20</td>
<td>63.46</td>
<td>110.70</td>
<td>78.91</td>
<td>63.46</td>
<td>78.91</td>
</tr>
<tr>
<td>666</td>
<td>20 20 20 20</td>
<td>60.68</td>
<td>110.70</td>
<td>78.91</td>
<td>60.68</td>
<td>78.91</td>
</tr>
<tr>
<td>1990</td>
<td>20 20 20 20</td>
<td>72.72</td>
<td>126.98</td>
<td>88.77</td>
<td>72.72</td>
<td>88.77</td>
</tr>
<tr>
<td>1991</td>
<td>20 20 20 20</td>
<td>72.26</td>
<td>123.73</td>
<td>88.77</td>
<td>72.26</td>
<td>88.77</td>
</tr>
<tr>
<td>1992</td>
<td>20 20 20 20</td>
<td>71.80</td>
<td>126.98</td>
<td>85.48</td>
<td>71.80</td>
<td>85.48</td>
</tr>
</tbody>
</table>
### Table 4.3: Experimental Results Due to Rotation, Loading and Heating

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Temperature at Various Points along the Length of the Direct Fired Rotary Kiln (°C)</th>
<th>Experimental Strain (µm/mm)</th>
<th>Transformed Strain (µm/mm)</th>
<th>Principal Strains (µm/mm)</th>
<th>Principal Stresses (MPa)</th>
<th>Orientation of the principal Strains (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Position 1</td>
<td>Position 2</td>
<td>Position 3</td>
<td>Position 4</td>
<td>$\varepsilon_{90}$</td>
<td>$\varepsilon_{45}$</td>
</tr>
<tr>
<td>1</td>
<td>22.3</td>
<td>23</td>
<td>23.4</td>
<td>22.2</td>
<td>89.40</td>
<td>140.01</td>
</tr>
<tr>
<td>2</td>
<td>22.3</td>
<td>22.3</td>
<td>23.4</td>
<td>22</td>
<td>88.01</td>
<td>136.75</td>
</tr>
<tr>
<td>3</td>
<td>22.3</td>
<td>21.6</td>
<td>23.4</td>
<td>21.7</td>
<td>88.47</td>
<td>140.01</td>
</tr>
<tr>
<td>4335</td>
<td>24.5</td>
<td>24.6</td>
<td>25.8</td>
<td>24.8</td>
<td>134.33</td>
<td>201.87</td>
</tr>
<tr>
<td>4336</td>
<td>24.5</td>
<td>24.5</td>
<td>25.8</td>
<td>24.8</td>
<td>135.26</td>
<td>198.61</td>
</tr>
<tr>
<td>4337</td>
<td>24.5</td>
<td>24.6</td>
<td>25.7</td>
<td>24.8</td>
<td>133.40</td>
<td>201.87</td>
</tr>
<tr>
<td>13160</td>
<td>31.3</td>
<td>38.3</td>
<td>33</td>
<td>47.4</td>
<td>227.90</td>
<td>325.60</td>
</tr>
<tr>
<td>13161</td>
<td>31.3</td>
<td>38.6</td>
<td>33</td>
<td>47.5</td>
<td>226.51</td>
<td>325.60</td>
</tr>
<tr>
<td>13162</td>
<td>31.5</td>
<td>38.1</td>
<td>33.2</td>
<td>47.5</td>
<td>225.12</td>
<td>325.60</td>
</tr>
</tbody>
</table>

### Table 4.4: Experimental Validation Data

<table>
<thead>
<tr>
<th></th>
<th>Maximum Principal Stress (MPa)</th>
<th>Minimum Principal Stress (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Stress Value for the Load Case (1)</td>
<td>12.2</td>
<td>3.77</td>
</tr>
<tr>
<td>Average Stress Value for the Load Case (2)</td>
<td>27.2</td>
<td>14.1</td>
</tr>
<tr>
<td>Average Stress Value for the Load Case (3)</td>
<td>52.6</td>
<td>25.9</td>
</tr>
</tbody>
</table>
CHAPTER 4.0: EXPERIMENTAL RESULTS

4.3.6 Results Due to Rotation

From investigating the measured strain in Figure 4.4, it is evident that the lateral strain on the plane of measurement is greater in magnitude than the longitudinal strain and the circumferential strain. By investigating the longitudinal and circumferential strains, the kiln drum may be undergoing slight bending as the kiln rotates. Even though the lateral strain is greater in magnitude, the measured longitudinal strain displays larger amplitudes of compressive strains and tensile strains, which means that the stress state of the kiln’s structural behaviour experiences its peak tensile and compressive stress in the longitudinal direction. This was expected since, according to Pazand [47], kilns experience most of their deflection in-between the rider ring supports. Pazand [47] stated that kilns may be modelled as simply supported beams and according to beam theory, a simply supported beam will experience a maximum deflection between the points of support. Since this holds true, the beam will experience maximum tensile and compressive stress in the centre. Since tensile and compressive stresses are evident in the results, the kiln experiences a small amount of structural plastic deformation as the kiln rotates. This means the kiln’s structural behaviour is experiencing constant change in shape without failing. Therefore, the kiln is behaving elastically. By investigating Figures 4.5 and 4.6 in terms of the principal stresses, and by taking the absolute average value for the entire run time, the maximum principal stress is 3.24 times greater than the minimum principal stress for the load case when the kiln rotates.

4.3.7 Results Due to Rotation and Loading

From Figure 4.8 and 4.9, it was evident that the added load from the platinum concentrate had an effect on the structural behaviour of the kiln in terms of stresses and strains in the measurement plain. The absolute average of the maximum and minimum principal stresses, for the load case when the kiln rotates and is loaded with process material, is 27.2 MPa and 14.1 MPa respectively. The absolute average of the maximum and minimum principal stresses, for the load case when the kiln rotated under its own weight, was 12.2 MPa and 3.77 MPa respectively. Therefore, it is evident that the added load had an effect on the structural behaviour of the kiln since the maximum principal stress in this load case was 2.3 times greater than for the load case when the kiln rotated under its own weight only. The minimum principal stress is 4 times greater than the minimum principal stress in the load case when the kiln rotated. The trend line for Figure 4.7, in terms of measured strains, follows the same behaviour as it did for the load case when the kiln rotated under its own weight. As in the load case when the kiln was under rotational forces and self-weight, the lateral strain is the largest in terms of magnitude for the load case with added load. By comparing Figure 4.7 to Figure 4.4, the longitudinal strain in Figure 4.4 experiences more frequent amplitudes of tensile and compressive strains. Whereas, in Figure 4.7 the longitudinal strain, in terms of compressive and tensile strains, occur less frequent. The possible reasoning to why the structural response behaves in this manner may be due to the fact that the platinum concentrate is churning within the kiln as it rotates and it experiences less vibrations due to the added load.
4.3.8 Results Due to Rotation, Loading and Heating

The temperature profile that the kiln experienced on the inner surface of the refractory lining and the outer shell of the kiln is shown in Figures 4.11 and 4.12. By investigating Figure 4.11 and Figure 4.13 simultaneously, the measured strain in the longitudinal directional experienced more frequent fluctuations in tensile and compressive strains for a short period in time. The explanation for this behaviour is due to the kiln's structural response to the rapid increase in temperature. At this point in time, the temperature started to increase rapidly from 71.2 °C and 476.6 °C, as recorded by thermocouple 3. The shell temperature at this point increased from 23.2 °C and 24.6 °C as recorded by thermocouple 4. The reasoning for the large variation in the measured strain was due to the fact that the refractory materials began to thermally expand, which had a direct influence on the kilns structural response to an increase in temperature gradient inside the kiln. The expansion of the refractory material caused the shell of the kiln to experience compressive forces in the circumferential and tensile forces in the longitudinal direction. After the rapid increase in temperature, the structural response of the kiln, in terms of compressive and tensile stresses, reached an almost steady state behaviour as shown in Figure 4.9. The largest magnitude between the largest peak (tensile strain) and the largest trough (compressive strain) was 1 MPa for the maximum and for the minimum principal stresses. The increase in the absolute average of the maximum and minimum principal stresses for the load case when the kiln rotated with added weight and was influenced by temperature, was two times greater than for the load case involving added weight and rotation.

4.4 Concluding Remarks

Chapter 4.0 presented the experimental results obtained for the different load cases that the direct-fired rotary kiln pilot plant was subjected to. Strain measurements were recorded for three load cases, namely (1) rotation, (2) rotation and loading and (3) rotation, loading and temperature change. The maximum and minimum principal stresses were calculated from the measured strains gathered from the experiment. From the experimental results, the structural response of the kiln increase in terms of measure strain and stress with respect to the different load cases. The load case involving heat recorded the largest magnitude in principal stress and induced strain. From the investigation, time, extra load and heat have a direct influence on the structural behaviour on the direct-fired rotary kiln pilot plant. Chapter 5.0 will present the transient numerical model using Abaqus and then validating the model by using the experimental data.
CHAPTER 5.0: NUMERICAL ANALYSIS OF A DIRECT FIRED ROTARY KILN

5.1 General Remarks

Chapter 4.0 examined the structural behaviour of the direct-fired rotary kiln pilot plant through experimentally measured strains for three different load cases, namely (1) rotation under its own weight, (2) rotation under its own weight and the added weight of the platinum concentrate and (3) rotation under its own weight, added weight of the platinum concentrate and heat. The experimentally determined principal stresses for each load case will be used to validate the transient numerical model developed and presented in this chapter. Two numerical models were developed and validated using the experimentally measured data. After validation of the numerical model, the heat parameter and the fill percentage were varied to further investigate the structural behaviour of the kiln.

5.2 The Finite Element Analysis

Abaqus/CAE (complete Abaqus environment) version 6.14-1 [76] was used to simulate the mechanical behaviour of the direct-fired rotary kiln pilot plant for two different load cases, namely (1) loading and rotation and (2) rotation, loading and heating. The main purpose was to determine the stress state of the direct-fired rotary kiln in the ideal case and use the experimentally determined principal stresses to validate the transient numerical model. The model used in analysing the direct-fired rotary kiln pilot plant is described in the following sections.

5.2.1 Geometry

The dimensions for the separate components used in the model will be defined and explained separately. The geometry of the direct-fired rotary kiln pilot plant was drawn and modelled in Solidworks 2014 [77]. The individual components were then converted to STEP AP 203 format to enable the individual parts to be imported into Abaqus CAE. The dimensions of the individual components were supplied by Drytech International Pty. Ltd. The mechanical drawings used to generate the models are presented in Appendix A.01.

5.2.1.1 Direct-Fired Rotary Kiln Shell

The kiln shell comprises of three main separate components, namely the inlet housing, outlet housing and the shell body. An overview of the operation of the pilot plant kiln is as follows. The inlet housing acts as the combustion chamber since it houses the heat source used for heating the process air. The outlet housing connects the rotary kiln to the ducting which leads to the off gas system comprising of a cyclone and baghouse. The kiln body contains the process material, which in this case is platinum concentrate. The inlet housing and the outlet housing are stationary during operation while the shell
body rotates. To simplify the geometry and to minimise computational time, the kiln shell was modelled as one complete piece. Figure 5.1 presents the geometry of the kiln shell. The overall length of the kiln shell is 2,733 mm with a diameter of 1,096 mm.

5.2.1.2 Refractory Lining

The refractory lining is made of castable refractory brick and a layer of concrete to secure the bricks within the kiln shell. The refractory lining comprises of three individual components, namely the refractory for the inlet housing, the refractory for the outlet housing and the refractory for the kiln shell. In order to minimise computational time, the refractory was modelled as one component with the same material properties. Figure 5.2 displays the geometry of the refractory lining. The lining has a thickness of 290 mm on the main kiln shell section with an inner diameter of 500 mm for processing the material.
5.2.1.3 Rider Ring

The rider ring and the support shoes are constructed from EN 8. There is a total of twelve support shoes holding the rider ring in place, concentric to the shell. The shoes are spaced 30° apart from one another. To minimise computation time, each rider ring and their respective support shoes were modelled as one component. The support shoes are welded to the outer shell of the pilot plant kiln. For the numerical model, a perfect weld joint of 100% joint efficiency is assumed. Figure 5.3 presents the geometry of the rider ring and support shoe assembly. The rider ring has an outer diameter of 1,301 mm with a thickness of 60 mm.

5.2.1.4 Drive Sprocket

The drive sprocket is used to drive and rotate the kiln. The drive sprocket is linked by a chain to the pinion sprocket mounted on the motor. A tensioner sprocket is coupled to the arrangement to minimise slack on the chain. In order to optimise computation time, the drive sprocket was simply modelled as a thin ring. The thin ring has thin plates welded to the outer surface of the kiln shell. A perfect weld joint is assumed for the numerical model. Figure 5.4 displays the geometry of the drive sprocket assembly. The drive sprocket has an outer diameter of 1,334 mm and a thickness of 35 mm including the welded plates.
Other components, such as the trunnions, support structure, chain and motor were not included in the model. This was to minimise computation time. Furthermore, the mentioned components have no direct influence on the critical stresses experienced by the kiln shell. The influences of some of the emitted components were incorporated into the numerical model as either boundary conditions or load conditions.

5.3 Material Properties

The material properties of each individual component was discussed in Section 3.3. This section will describe how the material properties were applied to the model. Table 5.1 represents the material properties of the individual components used in the numerical model.
Table 5.1: Material Properties as Assigned to the Individual Components in the Numerical Model

<table>
<thead>
<tr>
<th>Material</th>
<th>Assigned Component</th>
<th>Conductivity (W/m.K)</th>
<th>Density (kg/m³)</th>
<th>Young's Modulus (GPa)</th>
<th>Poisson's Ratio</th>
<th>Thermal Expansion (E-6/K)</th>
<th>Johnson and Cook Values</th>
<th>Melting Temperature (°C)</th>
<th>Specific Heat (J/kg.K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S 355 JR</td>
<td>Shell</td>
<td>25</td>
<td>7,850</td>
<td>200</td>
<td>0.3</td>
<td>10</td>
<td>A=217 MPa B= 234 MPa N= 0.643 M=1</td>
<td>1,510</td>
<td>460</td>
</tr>
<tr>
<td>EN 8</td>
<td>Rider rings; Sprocket</td>
<td>54</td>
<td>7,850</td>
<td>200</td>
<td>0.3</td>
<td>10</td>
<td>A=217 MPa B= 234 MPa N= 0.643 M=1</td>
<td>1,510</td>
<td>460</td>
</tr>
<tr>
<td>Firebrick</td>
<td>Refractory</td>
<td>0.4</td>
<td>1,100</td>
<td>3.69</td>
<td>0.19</td>
<td></td>
<td></td>
<td>110</td>
<td></td>
</tr>
</tbody>
</table>

5.4  Numerical Model Constraints

There are two types of non-linear analysis that may be done using Abaqus, namely Abaqus/Standard and Abaqus/Explicit. To determine whether to use Abaqus/standard or to use Abaqus/Explicit depends on the smoothness of the solution. It may not be possible to obtain an efficient solution with Abaqus/Standard if there are significant discontinuities in the solution [78]. Therefore, the numerical model for the direct-fired rotary kiln pilot plant was analysed using Abaqus/Explicit, due to the size of the model, complexity of the model, anticipated non-linear behaviour and the level of accuracy required for validation of the numerical model to the experimental stress data.

Different interactions were assigned to the separate components and interfacing regions between the components. The interactions are required to develop the numerical model to be a representative of the real behaviour of the pilot plant kiln.

5.4.1 Boundary Conditions

The interactions between the interfacing regions of the components are as follows:

1. Refractory Outer Surface and Kiln Shell Inner Surface
   The above mentioned components within the assembly were modelled with a general contact in explicit dynamic. Surface-to-surface discretization method considers the shape of both the master surface and slave surface when defining the contact constraints [78]. The shell of the kiln was chosen as the master surface and the refractory lining as the slave surface. A “rough” condition was applied to the interfacing region to allow no slip between these two surfaces. For the analysis including the temperature input, a boundary condition of the maximum shell temperature inner refractory lining was applied on the respective surfaces. This allowed the numerical model to reach its maximum temperatures on the mentioned surfaces.
2. Rider Rings and Drive Sprocket to the Outer Surface of the Kiln Shell
   Since the above mentioned components are welded to the pilot plant kiln outer shell, and all
   the individual components are constructed out of mild steel with almost identical material
   and mechanical properties, a tie constraint was applied which ties the surfaces together.

The boundary conditions applied in the numerical model were defined to simulate the behaviour of
the real life pilot plant. Since the direct-fired rotary kiln pilot plant is supported by four rollers on each
side of the two rider rings, the rollers will be simulated by the use of appropriate boundary conditions.
On the burner side, the rollers have “lips” which prevents the rotary kiln from slipping off its supports
during thermal expansion and rotation. These rollers were designed to act as thrust rollers. On the
discharge end of the kiln, the rollers were without guides allowing the kiln to expand and contract in
the longitudinal direction. To simulate these rollers, the boundary conditions were chosen as follows:

1. When facing the burner inlet on the inlet housing, on the right hand side of the rider ring
   closest to the drive sprocket, the simulated boundary conditions were used to constrain any
   movement in the x, y and z direction but allowing the rotational degrees of freedom to be
   unconstrained so that the kiln is able to deform.
2. On the left hand side of the same rider ring closest to the drive sprocket, the vertical (y-
   direction) and longitudinal (z-direction) were constrained to prevent the kiln from moving
   vertically and to prevent the kiln from expanding or contracting in the longitudinal direction.
3. On the left hand side of the rider ring closest to the discharge end of the kiln when facing the
   outlet housing, the vertical (y-direction) and lateral (x-direction) were constrained. This
   prevented the kiln from moving vertically as well as, preventing the kiln to deform laterally.
4. On the right hand side of the same rider ring, the kiln was constrained in the vertical (y-
   direction) which prevented the kiln from moving vertically. The respective boundary
   conditions are presented in Table 5.2.

Table 5.2: Boundary Conditions for the Numerical Model of the Pilot Plant Kiln

<table>
<thead>
<tr>
<th>Rider Ring</th>
<th>Lipped Roller One</th>
<th>Lipped Roller Two</th>
<th>Free Roller One</th>
<th>Free Roller Two</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rider ring nearest the burner</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>x, y and z direction</td>
<td>y and z direction constrained; x direction unconstrained; rotation unconstrained</td>
<td>Not applicable</td>
<td>Not applicable</td>
<td></td>
</tr>
<tr>
<td>rotation unconstrained</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rider ring furthest from the burner</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not applicable</td>
</tr>
<tr>
<td>rotation unconstrained</td>
</tr>
</tbody>
</table>
5.4.2 Loading Conditions

The extra load that the kiln experienced is due to the extra weight of the platinum concentrate. A total force of 1,535.76 N was applied on the inner surface of the kiln refractory lining. The applied load was simulated as a total distributed force over the inner surface of the refractory lining (middle section).

Due to angle of repose of the platinum concentrate, which was determined experimentally to be 30° [79], the material loading was simulated as shown in Figure 5.5. The load was applied downwards onto the refractory surface. All particles have a characteristic “static” or “poured” angle of repose. The angle of repose is defined as the maximum angle the material’s particles will sustain on a horizontal surface when poured out gently from a container. The value of the angle of repose depends on particle size, moisture content and surface coefficient of friction [80]. The angle of repose was determined experimentally by W. Grimm [79], a lab technician at Drytech International. W. Grimm’s [79] report has been attached in Appendix A.02.

The purpose of applying the angle of repose of the platinum concentrate was to simulate its behaviour inside the kiln as it rotated. A similar method was applied by Del Coz Diaz [45].

To summarise, the loads applied to the analysis are:

1. Gravity: Apply a downward acceleration of 9.81 m/s².
2. Material load: Apply a load of 1535.76 N downwards on to the refractory lining at 60° from the horizontal to simulate the rotation effect, angle of repose and frictional effect of platinum concentrate.
3. Heat: Temperature will be applied by using the temperature recorded from the experimental data gather at thermocouple 3, on the inner surface of the refractory, and thermocouple 4, on the outer shell of the kiln.
5.5 Mesh

The element type chosen for the analysis was a C3D8T element type. This is an explicit three dimensional brick tri-linear element most commonly applied to coupled temperature displacement problems. Each element has eight nodes associated with it. The active degrees of freedom associated with the element are 1 (x-direction), 2 (y-direction), 3 (z-direction) and 11 (temperature) [78].

5.5.1 Mesh Sensitivity

One of the most important steps in a finite element analysis is the mesh sensitivity study. Mesh sensitivity is a process of optimising the model to get the best possible and most accurate results from the numerical model. Finite element analysis is only an approximate solution, therefore the way in which the problem is discretized affects the accuracy of the solution [34]. There are two ways in which the accuracy of the model may be increased, namely h-refinement and p-refinement. H-refinement improves the accuracy of the results by utilising a finer mesh of the same element type. The P-refinement method improves the accuracy of the model by using the same type of mesh but using higher order interpolation function [81]. Therefore, the difference between the two methods is that the H-refinement method uses a large amount of simple elements, where the P-refinement method uses only a few complex elements.

The strain gauge, during the experimental procedure, followed a circumferential path on the outer shell of the kiln. In order to capture the stress state of the kiln in the numerical model, and to keep the results from the numerical model as close as possible to the experimental model, the same path will be followed. Rough calculations, applying simply supported beam theory [47], were done in Appendix A.03. The calculations confirmed that the maximum bending moment occurs between the two rider rings and therefore, it is expected that the maximum stress will occur in this region. The mesh sensitivity study was done by applying a load of 1,535.76 N, as described before, with a gravitational acceleration of \(9.81 \text{ m/s}^2\). Heat was not included in the mesh sensitivity study.

The mesh sensitivity study was done in the region between the two rider rings to capture the stress state at the centre of the kiln. The refractory was also refined in this region, so that the nodes on the shell would be directly coupled to the refractory nodes and therefore, transferring its mechanical behaviour to the nodes on the shell. The refined mesh area was studied by using the following element sizes 0.2, 0.15, 0.1, 0.075, 0.05, 0.025, 0.02 and 0.015 m. The path of the strain gauge is illustrated in Figure 5.6. At the point where the results from the finite element analysis does not differ significantly anymore, or in other words, the results start to converge, then there is no further need to optimise the mesh. However, increasing the number of elements increases computational time. Therefore, a balance has to be struck between accuracy and computational time.
5.5.2 Mesh Sensitivity Results

Table 5.3 illustrates the amount of elements for each simulation corresponding to the element sizes selected including the time it took for each simulation. The results for the mesh sensitivity study is shown graphically in Figure 5.7.

Table 5.3: Mesh Sensitivity Simulation Results

<table>
<thead>
<tr>
<th>Mesh Size (m)</th>
<th>Simulation Wall Time</th>
<th>Total number of elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>11 hours 50 min and 23 sec</td>
<td>10,203</td>
</tr>
<tr>
<td>0.15</td>
<td>11 hours 46 min and 13 sec</td>
<td>10,561</td>
</tr>
<tr>
<td>0.1</td>
<td>12 hours 8 min and 40 sec</td>
<td>11,209</td>
</tr>
<tr>
<td>0.075</td>
<td>13 hours 10 min and 40 sec</td>
<td>11,789</td>
</tr>
<tr>
<td>0.05</td>
<td>13 hours 52 min and 17 sec</td>
<td>13,008</td>
</tr>
<tr>
<td>0.025</td>
<td>16 hours 59 min and 35 sec</td>
<td>16,674</td>
</tr>
<tr>
<td>0.02</td>
<td>18 hours 46 min and 40 sec</td>
<td>18,464</td>
</tr>
<tr>
<td>0.015</td>
<td>20 hours 21 min and 5 sec</td>
<td>21,559</td>
</tr>
</tbody>
</table>
5.5.3 Discussion of Mesh Sensitivity Results

From Table 5.3 and Figure 5.7, there is a clear indication that meshing the drum and refractory with different element sizes has a notable impact on the computational time to complete a single simulation. The mesh size also affects the number of elements and the structural behaviour, in terms of principal stresses induced in the kiln. As the element size decreases, the computational time increases.

From Figure 5.7, it can be seen that there is a sudden increase in the maximum principal stress when the element size is 50 mm. As the element size for the mesh decreases, it seems that the results start to converge and then suddenly the result increases to a maximum of 0.552 MPa and then drops down to a maximum of 0.530 MPa where the results start to converge. At the element size of 50 mm, more equations are developed within the simulation since there are more elements, therefore increasing the accuracy of the results according to the H-refinement method. Therefore, further mesh refinement yielded converging results. The average maximum principal stress along the path with an element size of 25 mm was 0.528 MPa.

Therefore, from the mesh sensitivity analysis, a mesh size of 25 mm quadratic hexahedral elements would be adequate for further simulation of the kiln. The final meshed model is shown in Figure 5.8. From Figure 5.8, it can be seen that element sizes differ between the kiln shell, the support rings, the drive sprocket and the refractory. The mesh sizes for each component in the analysis is shown in Figure 5.8 to Figure 5.10.
CHAPTER 5.0: NUMERICAL ANALYSIS

Figure 5.8: Final Mesh Size of 25 mm for the Numerical Modelling

Figure 5.9: Element Size of the Model
In order to understand the structural behaviour of the direct-fired rotary kiln under mechanical and thermal load, a thermal analysis was conducted on the pilot plant. Holloway [82] investigated the thermal behaviour of the direct-fired rotary kiln pilot plant at Drytech by using an experimentally validated computational fluid dynamics (CFD) model. Holloway mainly focused on two of the main heat transfer mechanisms, namely convection and conduction.

From Holloway's experimental data, the author discovered that the average rate of heat transfer, between the process material and the kiln outer shell, were negative values. This implied that heat was transferred from a hotter surface (process material) to the cooler surface (kiln wall). The average heat transfer coefficient between the process material and the kiln wall was -3.25 KW/m$^2$. This relates to theory since energy transfer occurs from a higher temperature to a lower temperature [82].

Maximum heat transfer occurred near the burner end and at a point after the second rider ring, near the outlet housing. Holloway explained that the possible reasoning behind the temperature increase, near the burner, was due to the decrease in velocity of the process material [82].

Holloway [82] investigated the influences that the mass flow rate of air into the burner had on the numerical model. Holloway discovered that by increasing the mass flow rate of air into the burner, there is a decrease in the temperature of the kiln wall. The author explained that the possible reasoning behind the lower temperatures on the kiln wall was because the combustion gases were exiting the kiln too quick with low residence time inside the kiln. This means that there was not enough time for the heat to transfer from the combustion gases to the process material. The temperature profile was simulated and is shown in Figure 5.11.
By using the information gathered by Holloway [82] and by Arad [23], where the author described that radiation is the main mode of heat transfer in a rotary kiln, a thermal stress study may be investigated to determine the influences of a temperature gradient on the structural response of the kiln in the numerical model.

5.6.1 Abaqus Thermal Stress Model

5.6.1.2 Transient Heat transfer

The purpose of conducting a heat transfer analysis is to determine if the model is able to depict the thermal results obtained from the experimental results. The kiln had to be modelled numerically to portray the non-ideal case in an ideal environment. A reference temperature for the absolute zero temperature was taken as -273.15 °C and the Stefan-Boltzmann constant used in the numerical model was 5.67 E-08 W/m²K⁴.

Since the temperature of the flame was not measured, the temperature measured on the refractory from the experimental data will be used in the numerical model. From Figure 5.11, the maximum temperature that the kiln experiences within the direct-fired rotary kiln is at the point closest to the first support rider ring nearest to the burner. By investigating Figure 4.11, thermocouple 3 maintains a high constant temperature and reaches 871.2 °C at its maximum. Therefore, the data captured for thermocouple 3 will be applied to the inner surface of the refractory. The refractory will be allowed to heat up in the model from ambient (21.5 °C) to its maximum through 1316 increments.

Since the air temperature, particle movement of the platinum concentrate and gas velocity was not experimentally determined, only conduction will be considered for the numerical analysis. As Mujumdar [24] explained, conductive heat transfer occurs between the refractory lining and the kiln shell.

Material characteristics of the individual components were defined in Table 5.1. The numerical model required a contact property for conductive heat transfer. The conductive heat transfer coefficient used for the numerical analysis was that of the mild steel shell (25 W/m.K), since conduction occurs between the refractory and the shell. The longitudinal cross section of the direct-fired rotary kiln pilot plant is shown in Figure 5.12 for the transient heat transfer model considering conduction between the refractory and the kiln wall.
Figure 5.12: Temperature Distribution from the Centre of the kiln to the Outer shell of the Kiln

Figure 5.13 illustrates the temperature distribution from the centre of the kiln, where the flame is expected, to the outer surface of the kiln shell.

Figure 5.13: Temperature Distribution from the Centre of the Kiln to the Outer Shell of the Kiln
5.6.1.3 Kiln Structural Response Analyses

From the transient heat transfer analysis on the direct-fired rotary kiln pilot plant, the structural behaviour in response to added weight and heat may be modelled to investigate the stress state of the kiln. A boundary condition was set for the inner refractory temperature, in other words, the maximum temperature recorded by thermocouple 3 during the experimental procedure. The reason why transient heat transfer was not incorporated into the model was because the explicit temperature displacement step does not allow it. Therefore, the same inputs from the transient heat transfer model was used to investigate the structural behaviour due to mechanical and thermal stresses.

The maximum flame temperature used on the inner surface of the kiln was $871.2\, ^\circ\text{C}$. It was also noted, from the transient heat transfer model, that the temperature of the shell surface did not reach the same temperature as the recorded temperature data from thermocouple 4. Figure 5.13 illustrates the maximum shell temperature the kiln experienced during the numerical model, which was $25.1\, ^\circ\text{C}$, whereas the experimental temperature at thermocouple 4 reached a maximum of $38.2\, ^\circ\text{C}$. Therefore, in order to get correct results, a temperature boundary condition was applied to the outer shell surface to represent the maximum measured temperature. The boundary condition was set to a value of $38.2\, ^\circ\text{C}$ on the outer wall to make sure the shell temperature displays the same value as it did in the experimental investigation. The purpose of this was to investigate how the temperature increase, from $21.5\, ^\circ\text{C}$ to $38.2\, ^\circ\text{C}$, influenced the structural behaviour of the kiln.

The numerical model study included the loads due to self-weight, load added by the platinum concentrate and the heat that were applied in a singular explicit temperature-displacement step. The visual representation for the maximum principal stress distribution is shown in Figure 5.14 and the results for the maximum and minimum principal stresses are graphically presented in Figure 5.15, followed by Table 5.4 indicating the average maximum and minimum principal stresses along the chosen circumferential path on the kiln outer shell.
5.6.1.4 Numerical Model Discussion

By comparing Table 5.4 to Table 4.4, there is a clear indication that the principal stress state on the circumferential path in the numerical model is less than the experimentally determined principal stresses. Even though the numerical model displayed tensile (peaks) and compressive (Troughs) stresses, the magnitude of the principal stress is less.

From Figure 5.15, the minimum principal stress is almost a mirror image of the maximum principal stress. The percentage error between the experimental data and the numerical data was calculated by taking the average principal stress from the experimental data, as defined in Table 4.4, for the entire process involving heat and the average principal stress from the numerical model. The percentage error was calculated as follows:

Maximum principal stress:

\[
\%error = \frac{|52.6 - 4.32|}{52.6} \times 100
\]

\[
\%error = 91.79\%
\]
Minimum principal stress:

\[
\%\text{error} = \frac{|25.9 - 4.4|}{25.9} \times 100
\]

\[
\%\text{error} = 83.01\%
\]

The percentage error shows a large discrepancy between the experimental results and the model. Steady state hand calculations, using thick wall theory, were done to get an understanding of the principal stresses that occur on the outer surface of the kiln due to the thermal expansion of the refractory on the shell of the kiln. From the calculations, the maximum principal stress was calculated as 168.53 MPa and a minimum principal stress of 105.34 kPa. This indicates that an error could have occurred with the calibration of the nodes to capture the strain rate of the kiln and an error could have occurred with the numerical model, where the interactions between the different components were not captured.

The way in which the accuracy of the experimental results could be increased is by performing simple calibration experiments on simple elements, such as a simply supported beam, with a known value. The way in which the accuracy of the model could be increased is by modelling the refractory and the shell of the kiln as one single component in order to remove the discontinuity between the components. A partitioning step could be imposed to separate the kiln shell and the refractory to assign the respective material properties. By doing this, the temperature distribution through the walls of the kiln and the applied load, from the platinum concentrate, could accurately depict the influence that these inputs would have on the structural response, when compared to the experimental data. To further increase the accuracy of the model, the element sizes for the entire kiln shell should be 25 mm. This will allow the elements to behave in the same manner as every other element on the shell.
5.6.2 Parameter Influence on the Numerical Model

Since platinum is considered as one of the heaviest minerals found on earth and the kiln was practically filled to where the flame ejected from the burner, it would be unpractical to analyse the direct-fired kiln with more material. Therefore, the material feed will be decreased within the kiln, assuming the same material properties for platinum concentrate. The material properties were determined experimentally, as stated, by W. Grimm through a drying test conducted at Drytech International. Table 5.5 presents practical fill percentages that the direct-fired kiln was designed for. According to Table 5.5, the direct-fired kiln was filled to a percentage of 38.68%. Therefore, the model was used to simulate a fill percentage of 30, 20, 15 and 10% without the influence of heat. The results will give a clear indication of how the added weight inside the kiln affects the structural behaviour of the kiln.

Table 5.5: Fill Percentage Variation

<table>
<thead>
<tr>
<th>Percentage Fill (%)</th>
<th>Cross Sectional Area (m²)</th>
<th>Length (m)</th>
<th>Total Volume of Drum (kg/m³)</th>
<th>Mass of Platinum in Drum (kg)</th>
<th>Weight of Platinum (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.196</td>
<td>1.45</td>
<td>0.28</td>
<td>404.72</td>
<td>3970.27</td>
</tr>
<tr>
<td>50</td>
<td>0.098</td>
<td>1.45</td>
<td>0.14</td>
<td>202.36</td>
<td>1985.13</td>
</tr>
<tr>
<td>45</td>
<td>0.088</td>
<td>1.45</td>
<td>0.13</td>
<td>182.12</td>
<td>1786.62</td>
</tr>
<tr>
<td>40</td>
<td>0.079</td>
<td>1.45</td>
<td>0.11</td>
<td>161.89</td>
<td>1588.11</td>
</tr>
<tr>
<td>38.68</td>
<td>0.076</td>
<td>1.45</td>
<td>0.11</td>
<td>156.55</td>
<td>1535.76</td>
</tr>
<tr>
<td>35</td>
<td>0.069</td>
<td>1.45</td>
<td>0.10</td>
<td>141.65</td>
<td>1389.59</td>
</tr>
<tr>
<td>30</td>
<td>0.059</td>
<td>1.45</td>
<td>0.09</td>
<td>121.42</td>
<td>1191.08</td>
</tr>
<tr>
<td>25</td>
<td>0.049</td>
<td>1.45</td>
<td>0.07</td>
<td>101.18</td>
<td>992.57</td>
</tr>
<tr>
<td>20</td>
<td>0.039</td>
<td>1.45</td>
<td>0.06</td>
<td>80.94</td>
<td>794.05</td>
</tr>
<tr>
<td>15</td>
<td>0.029</td>
<td>1.45</td>
<td>0.04</td>
<td>60.71</td>
<td>595.54</td>
</tr>
<tr>
<td>10</td>
<td>0.020</td>
<td>1.45</td>
<td>0.03</td>
<td>40.47</td>
<td>397.03</td>
</tr>
</tbody>
</table>

To determine whether the temperature within the kiln and on the shell of the kiln had a significant influence on the structural behaviour of the direct-fired kiln, the temperature will also be varied to match the temperature of the direct flame produced by the burner. The material in the direct-fired kiln will be kept constant at the same weight as measured for the experimental data, in other words, the weight inside the kiln will be 1535.76 N (38.68%). The temperature on the inner surface of the refractory lining and on the kiln outer shell will be varied for the numerical simulation. The values used for the temperature on the inside of the kiln refractory and the kiln shell is shown in Table 5.6.

Table 5.6: Temperature Variation

<table>
<thead>
<tr>
<th>Shell Temperature</th>
<th>Refractory Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 °C</td>
<td>950 °C</td>
</tr>
<tr>
<td>60 °C</td>
<td>960 °C</td>
</tr>
</tbody>
</table>
5.6.2.2 Parameter Change Results

Figure 5.17 presents the results obtained from the numerical model with respect to the change in fill percentage. Figure 5.18 shows the effects of fill percentage on the maximum induced stress. The results for the stress analysis were recorded as before, by selecting a circumferential path on the outer shell surface.

From Figure 5.17 and Figure 5.18, there is a clear indication that the fill percentage has an influence on the stress behaviour experienced by the kiln. From Figure 5.18, it was determined that at 38.86% fill the kiln experienced the largest amount of principal stress since the kiln was filled to its maximum capacity without blocking the flame. From the results, it can be confirmed that the stress behaviour within the kiln is proportional to the percentage fill and therefore, weight added to the kiln. As weight is added to the kiln, the kiln will experience an increase in bending. As the kiln bends, the surface of the kiln, where the load is applied, experiences tensile stresses, whereas on the opposite side the kiln will experience compressive stresses on its surface. This will cause the kiln to elongate on the surface with the applied force and contract on the opposite surface. These surfaces will vary as the kiln rotates.

By investigating points 6 to 11 on Figure 5.17, there is a clear indication that there is an increased level of principal stress due to the position of the material modelled in the kiln. Since the material is acting on the inner walls of the refractory, which forces the refractory to push against the kiln shell, the shell experiences compressive and tensile stresses and strains. The compressive and tensile stresses are clearly seen in the fluctuations in Figure 5.17. The level of principal stress, in terms of the fill percentage at maximum capacity, was larger in magnitude when compared to the principal stress levels for the remaining fill percentages.

Figure 5.18 was used to illustrate how the stress decreases as a function of the percentage fill by investigating the average maximum principal stress of each circumferential path by the associated percentage fill. From 38.68% to 30% fill percentage, there is a large decrease in average principal stress when compared to 30% to 10%. The possible reason for this is due to less compressive forces acting on the kiln shell due to a decrease in load. Less added weight has an effect on the structural response of the kiln since it experiences less deflection in its structure.

![Figure 5.16: Influence of Fill Percentage on the Stress Behaviour of the Pilot Plant Kiln](image-url)
Figure 5.19 illustrates the structural response of the direct-fired rotary kiln due to an increase in temperature. From the figure, it was discovered that at a temperature of 60 °C on the kiln shell, the magnitudes of the compressive and tensile stresses increased. This was due to the structural stability being weakened by the increase in thermal load. The thermal load elongates the kiln’s shell in the longitudinal direction. There is a clear indication that the thermal stresses, and mechanical stresses due to the weight of the platinum concentrate, have an effect on the outer shell of the kiln. As the kiln elongates, the pressure applied by the platinum concentrate causes the kiln to deflect and bend. As the material load acts against the kiln, when under thermal stress, ovality is expected due to the decrease in the structural stiffness of the kiln. Even though the refractory within the kiln is expected to expand, the expansion is negligible due to its thermal expansion coefficient. This is expected since refractory material is designed to resist thermal shock [83].

Figure 5.20 illustrates the almost perfectly linear increase in maximum principal stress as a function of temperature. The maximum peak stress the kiln experienced at 38.2 °C was 10.74 MPa, whereas at a temperature of 60 °C on the kiln shell, the maximum stress experienced was 24.23 MPa. Therefore, there is an increase of 1.25 % at a temperature change from 38.2 to 60 °C. This correlates to the experimental data. As heat was introduced to the system during experimental data capturing, the average stress level for the load case involving added load due to weight, rotational load and thermal load was 52.6 MPa and therefore 4.3 times greater than the case for the load involving self-weight and rotational loads. From figure 5.20, there was a significant increase in stress between 50 and 60 °C than 38.2 to 50 °C. The reason why this may have occurred, is because the shell experiences elastic deformation in this temperature region.
CHAPTER 5.0: NUMERICAL ANALYSIS

Figure 5.18: Influence of Temperature Change on the Stress Behaviour of the Pilot Plant Kiln

Figure 5.19: Average Thermal Stress for each Temperature Change
5.7 Chapter Summary

Chapter 5 presented the numerical model developed to simulate the structural behaviour of the direct-fired rotary kiln pilot plant. The experimental data, from Chapter 4, was used to validate the numerical model. The numerical model displayed a similar response in structural behaviour to that of the experimental data, in terms of the stress and strain rate due to the different load conditions. When the results were compared, a large discrepancy occurred and could be due to miss calibration of the nodes during experimental data capturing and discontinuities within the numerical model. From the study, it was deduced that the stress state that the kiln experiences is influenced by different loads. In this case, the stress and strain state was influenced by the added weight from the platinum concentrate and generated thermal load. This means that the behaviour of the kiln’s structure changes for each load case. The fill percentage and the thermal load was varied for the model to get a better understanding of the structural behaviour of the kiln in response to the different load applications.
6.1 Background Remarks

The purpose of the investigation was to study the structural response of the kiln for three different load cases, namely (1) kiln under self-weight and rotation, (2) self-weight, added load and rotation and (3) self-weight, added load, heat load and rotation. A strain gauge rosette was used to experimentally capture the strain state of the outer shell of the kiln in the longitudinal direction, circumferential direction and at 45° to the axial direction. The experimental results were used to validate a transient numerical model of the pilot plant kiln generated in Abaqus/CAE 6.14 for the load cases highlighted above which also involved thermal load. The model was also used to gain a better understanding of the structural response of the kiln under the influence of different load cases.

6.2 Conclusion

Based on this investigation on the structural behaviour of the direct-fired rotary kiln pilot plant, the following conclusions may be deduced:

1. The maximum principal stresses the kiln experienced during the experimental phase for the three different load cases was 12.2, 27.2 and 52.6 MPa respectively.
2. The minimum principal stresses the kiln experienced during the experimental phase for the three different load cases was 3.77, 14.1 and 25.9 MPa respectively.
3. The maximum temperature that the kiln experienced for the load case including the thermal load, on the inner surface of the refractory, was 871.2 °C and 38.2 °C on the outer shell surface.
4. At the maximum temperatures, the stress and strain state of the kiln reached a steady state.
5. When investigating the strain state for the load case involving heat, the strain state in the longitudinal direction experienced large fluctuations in compressive and tensile strains due to the rapid increase in temperature inside the kiln.
6. The stress state, in terms of maximum principal stresses, increased by 55.14 % in the load case with added load when compared to the previous load case under rotation and self-weight. Therefore, the principal stress for the load case including the weight from the platinum concentrate increased due to the extra load.
7. When comparing load case (2) to load case (3), where a thermal load was applied, the principal stress experienced by kiln increased by 48.29 % and increased by 76.81 % when comparing load case (1) to load case (3).
8. From the experimental results, it was concluded that the structural behaviour is influenced by different load cases and can be witnessed by investigating the structural response of the kiln.
9. The transient numerical model of the direct-fired rotary kiln pilot plant displayed the same structural behaviour in terms of compressive and tensile stresses. At different points on the circumference of the outer kiln shell, depending on the point location, the kiln in the numerical model displayed compressive and tensile principal stresses.
10. The validation of the model using experimental results indicated an error of 91.79 % for the maximum principal stress and 83.01 % for the minimum principal stress.
11. Rough hand calculations were performed to determine a ball park principal stress on the shell of the kiln. A percentage error for the maximum principal stress with respect to the experimental data was 68.79 % and the percentage error for the maximum principal stress with respect to the numerical model data was 97.44 %. Therefore, a larger area occurred in the numerical model.

12. The error percentage indicates that the interactions between the different components and the mechanical behaviour of the components where not fully captured.

13. When comparing the principal stresses between the two modelled cases, the principal stress for the load case with the modelled heat transfer increased by 87.73 %.

14. When the fill percentage was varied from 10 % to 38.86 %, the stress the kiln experienced increased by 26.42 %.

15. As the temperature increased on the kiln shell from 38.2 °C to 60 °C, by maintaining a fill percentage of 38.86 %, the stress the kiln increased by 59.25 %.

6.3 Recommendations

To further develop the understanding of the structural response of kilns for the intended design loads, the following recommendations for future work may be introduced:

1. The material modelling of the materials used to construct the kiln should be based on actual mechanical tests performed on samples of the materials. The material properties to be determined include the Johnson and Cook material coefficients, thermal expansion coefficients, temperature transition zones and the elastic-plastic response of the materials.

2. The numerical model should be in more detail, especially at various sections and part junctions, to fully understand the behaviours of the kiln’s materials, interactions between the components and the structural behaviour of the entire thermal processing system for different load cases.

3. To model the process material behaviour, as the kiln rotates, in order to capture the influence of the process material churning in the kiln.

4. To perform experimental data capturing on a full-scale industrial kiln. This will give a true representation of the structural behaviour of direct-fired rotary kilns in service, accurately capturing the structural behaviour of the complex system.

5. To validate numerical model based on the experimental data captured for the full-scale industrial kiln, representing the true structural response of the kiln under normal service loads.
REFERENCES


REFERENCES


REFERENCES


[77] Solidworks, 2014.


REFERENCES


A.O. APPENDICES
A.01. Mechanical Drawings of the Rotary Kiln by Drytech International Pty. Ltd.
A.02. Report on Drying Platinum Concentrate by Mr. W. Grimm
Report on Drying Platinum Concentrate.  
Test 1460  
05/12/2008

The wet material was flash dried before it was roasted in the fluidised bed. The temperature of the gas heater, before the disintegrator, was kept constant at 730 °C. The feed rate of the screw was kept constant at 15 Hz. The particles leaving the disintegrator were sucked through the cyclone. The larger particles leaving the cyclone were fed to the fluidised bed.

The fluidised bed was packed with 29 kg of platinum concentrate to give a bed height of 200 mm before fluidisation. Air was supplied to the bed via a fan feeding the gas burner that was used to heat the bed. The fluidised bed was followed by another cyclone. The larger particles were collected in a drum underneath the cyclone. The smaller particles, once again, went to the baghouse.

The particles from both the drum and baghouse were collected for analysis.

The following parameters were established:

- Particle size of platinum concentrate: 0.6-1.2 mm
- Moisture content (wet material): 22% m/m w.b
- Bulk density, loose (Baghouse product): 550.75 kg/m³
- Bulk density, shaken (Baghouse product): 1024.4 kg/m³
- Bulk density, loose (Cyclone product): 1090.93 kg/m³
- Bulk density, loose (Cyclone product): 1421.52 kg/m³
- Angle of repose (Baghouse product): 29.5 °
- Angle of repose (Cyclone product): 31.33 °

- Duration of test: 167 min
- Wet material feed: 226.06 kg
- Dry material feed: 176.32 kg
- Wet feed rate: 1.35 kg/min
- Cyclone product: 3.10 kg
- Baghouse product: 137 kg
Overview of the test observations:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Min</th>
<th>Max</th>
<th>Avg.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom bed temperature (°C)</td>
<td>592</td>
<td>728</td>
<td>644</td>
</tr>
<tr>
<td>Top bed temperature</td>
<td>151</td>
<td>658</td>
<td>561</td>
</tr>
<tr>
<td>Free board temperature</td>
<td>83</td>
<td>140</td>
<td>102</td>
</tr>
<tr>
<td>Cyclone temperature</td>
<td>183</td>
<td>266</td>
<td>203</td>
</tr>
<tr>
<td>Baghouse temperature</td>
<td>48</td>
<td>56</td>
<td>51.3</td>
</tr>
<tr>
<td>Fluidizing velocity (m/s)</td>
<td>6</td>
<td>10</td>
<td>8.42</td>
</tr>
<tr>
<td>Bed dP (mmH2O)</td>
<td>170</td>
<td>290</td>
<td>248</td>
</tr>
<tr>
<td>O2 (%)</td>
<td>8.82</td>
<td>14.5</td>
<td>10.71</td>
</tr>
<tr>
<td>SO2 (ppm)</td>
<td>203</td>
<td>1695</td>
<td>518.3</td>
</tr>
<tr>
<td>CO (ppm)</td>
<td>44</td>
<td>9987</td>
<td>4832</td>
</tr>
<tr>
<td>CO2 (%)</td>
<td>4.24</td>
<td>7.56</td>
<td>6.41</td>
</tr>
<tr>
<td>Top temp (°C)</td>
<td>220</td>
<td>330</td>
<td>245</td>
</tr>
<tr>
<td>Venturi dP (Pa)</td>
<td>70</td>
<td>100</td>
<td>86.3</td>
</tr>
</tbody>
</table>

Particle size distribution:

<table>
<thead>
<tr>
<th>Size</th>
<th>Baghouse (%)</th>
<th>Cyclone (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt;212 µm</td>
<td>0.551</td>
<td>1.014</td>
</tr>
<tr>
<td>&gt;125 µm</td>
<td>0.551</td>
<td>1.018</td>
</tr>
<tr>
<td>&gt;75 µm</td>
<td>1.239</td>
<td>10.14</td>
</tr>
<tr>
<td>&lt;75 µm</td>
<td>97.52</td>
<td>87.77</td>
</tr>
</tbody>
</table>

After the bed fluidised, an increase in bed temperature was observed without altering the feed conditions. This, combined with the facts that both products (collected from the baghouse and cyclone) were discoloured and the presence of SO2 in the exhaust gas suggests that roasting did occur.

The bed did not remain fluidised throughout the run. Shortly after the exothermal reaction was observed, the bed collapsed. The pipe that fed the roaster was disassembled and it was blocked completely with material similar to that of the baghouse product. The fluidised bed was also emptied and it contained large particles, in excess of 3 mm.

High concentration of CO was observed in the exhaust gas. The cyclone product is magnetic.

Barnard, P.S  Grimm. W
Sinosich       P.R Eng 940393
A.03. Basic Hand Calculations – Bending Moment
Total volume of refractory = $V_{rt} = 1.78 \text{ m}^3$
Total volume of steel shell = $V_{st} = 0.12 \text{ m}^3$
Total volume of rider rings = $V_{rrt} = 0.015 \text{ m}^3 \times 2 = 0.03 \text{ m}^3$
Total volume of sprocket = $V_{spt} = 0.0077 \text{ m}^3$
Assume that two thirds of the refractory and shell weight acts in the centre of the kiln. Therefore:

$2/3 \times V_{rt} = 1.187 \text{ m}^3$ and $2/3 \times V_{st} = 0.08 \text{ m}^3$ and therefore the left hand side and the right hand side carry the difference.

$\frac{(1.78 \text{ m}^3 - 1.187 \text{ m}^3)}{2} = 0.296 \text{ m}^3$ and $\frac{(0.12 \text{ m}^3 - 0.08 \text{ m}^3)}{2} = 0.02 \text{ m}^3$

Therefore, it is assumed that the total weight calculated is distributed along the length of each segment. The total distributed weight may be calculated for the left hand side, the middle and the right hand side:

Left hand side:

$(0.02 + 0.0077) \times 7850 \text{ kg/m}^3 \times 9.81 \text{ m/s}^2 = 2.13 \text{ kN/m} - \text{Steel}$

$0.296 \times 1100 \text{ kg/m}^3 \times 9.81 \text{ m/s}^2 = 3.19 \text{ kN/m} - \text{Refractory}$

Total = 5.32 kN/m

Middle:

$(0.08 + 0.03) \times 1100 \text{ kg/m}^3 \times 9.81 \text{ m/s}^2 = 8.470 \text{ kN/m} - \text{Steel}$

$1.187 \times 1100 \text{ kg/m}^3 \times 9.81 \text{ m/s}^2 = 12.81 \text{ kN/m} - \text{Refractory}$

Total = 21.28 kN/m + 1.54 kN/m (due to material loading) = 22.82 kN/m
Right hand side:

\[ 0.02 \times 7850 \text{ kg/m}^3 \times 9.81 \text{ m/s}^2 = 1.54 \text{ kN/m} - \text{Steel} \]

\[ 0.296 \times 1100 \text{ kg/m}^3 \times 9.81 \text{ m/s}^2 = 3.19 \text{ kN/m} - \text{Refractory} \]

Total = 4.73 kN/m

Point loads:

Left:

\[ B \times h = 5.32 \text{ kN/m} \times 0.832 = 4.43 \text{ kN} \text{ acting at 0.416 m from the fixed support} \]

Middle:

\[ B \times h = 22.82 \text{ kN/m} \times 1.2 = 27.38 \text{ kN} \text{ acting at 0.6 m from the fixed support} \]

Right:

\[ B \times h = 4.73 \text{ kN/m} \times 0.701 = 3.32 \text{ kN} \text{ acting at 1.55 m from the fixed support} \]

Moments about \( R_y \):

\[ \Sigma M = 0 \text{ (Clockwise as positive)} \]

\[ = (0.416 \times 4.43) + (0.6 \times 27.38) - (R_{by} \times 1.2) + (1.55 \times 3.32) \]

\[ R_{by} = 19.51 \text{ kN} \]

Reaction forces:

\[ \Sigma F_x = 0 \]

\[ R_{ax} = 0 \]

\[ \Sigma F_y = 0 \]

\[ = R_{ay} + R_{by} - 4.43 \text{ kN} - 27.38 \text{ kN} - 3.32 \text{ kN} \]

\[ R_{ay} = 15.62 \text{ kN} \]
At x = 0.832 m
\[ \Sigma M = 0 \text{ (Clockwise as positive)} \]
\[ = 0.416 \times 4.43 - M_{0.83} \]
\[ M_{0.83} = 1.84 \text{ kN.m} \]

At x = 1.43 m
\[ \Sigma M = 0 \text{ (Clockwise as positive)} \]
\[ = 0.416 \times 4.43 - 15.862 \times 0.832 - M_{1.43} \]
\[ M_{1.43} = -11.35 \text{ kN.m} \]

At x = 2.032 m
\[ \Sigma M = 0 \text{ (Clockwise as positive)} \]
\[ = 0.416 \times 4.43 - 15.862 \times 0.832 + 1.43 \times 27.38 - M_{2.032} \]
\[ M_{2.032} = 27.79 \text{ kN.m} \]

At x = 2.38 m
\[ \Sigma M = 0 \text{ (Clockwise as positive)} \]
\[ = 0.416 \times 4.43 - 15.862 \times 0.832 + 1.43 \times 27.38 - 2.032 \times 19.51 - M_{2.38} \]
\[ M_{2.38} = -11.84 \text{ kN.m} \]
Therefore, my maximum bending moment and deflecting due to self-weight and added weight from the platinum concentrate is expected to be between the two rider rings.
A.04. Basic Hand Calculations – Principal Stress
Assume that the outer shell of the kiln is homogenous and isotropic throughout.

Assume that the only pressure working on the shell is due to thermal expansion of the refractory onto the shell due to a change in length and the loaded platinum concentrate.

Material properties:

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Refractory</th>
<th>Shell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poisson’s ratio</td>
<td>0.19</td>
<td>0.3</td>
</tr>
<tr>
<td>Elastic modulus (GPa)</td>
<td>3.96</td>
<td>200</td>
</tr>
<tr>
<td>Coefficient of linear expansion (x10⁶/K)</td>
<td>5.8</td>
<td>10</td>
</tr>
</tbody>
</table>

Ambient temperature = $T_a = 20 \degree C$

Shell temperature final = $T_{sf} = 47.5 \degree C$

Refractory temperature final = $T_{rf} = 871.2 \degree C$

Refractory Thickness = $Th_kr = 0.29 \text{ m}$

Shell Thickness = $Th ks = 0.008 \text{ m}$
Thermal expansion of the refractory cross section:

$$\Delta L = \alpha \Delta t L$$

$$\Delta L = (5.8 \times 10^{-6} / K) \times (871.2 - 20) \times (0.29)$$

$$\Delta L = 1.43 \times 10^{-3}$$

Thermal stress of the refractory:

$$\sigma_{\text{ref}} = E \varepsilon$$

$$\sigma_{\text{ref}} = (3.96 \text{ GPa}) \times (1.43 \times 10^{-3} \text{ m}/0.29)$$

$$\sigma_{\text{ref}} = 19.53 \text{ MPa}$$

Force exerted onto the shell:

$$F_{\text{ref}} = (\sigma_{\text{ref}} \times A_{\text{cross}}) + 1.54 \text{ kN (due to weight of platinum concentrate)}$$

$$F_{\text{ref}} = (19.53 \text{ MPa} \times (\pi (1.08^2 - 0.5^2)/4)) + 1.54 \text{ kN}$$

$$F_{\text{ref}} = 14.058 \text{ MN}$$

Pressure exerted onto shell:

Outer surface area of refractory:

$$A_{\text{ref} - \text{Outer}} = 2 \pi r_2 h_2$$

$$A_{\text{ref} - \text{Outer}} = 2 \pi (0.54) \times (1.976)$$

$$A_{\text{ref} - \text{Outer}} = 6.074 \text{ m}^2$$

$$P = \frac{F_{\text{ref}}}{A_{\text{ref} - \text{Outer}}}$$

$$P = 14.058 \text{ MN} / 6.074 \text{ m}^2$$

$$P = 2.31 \text{ MPa}$$

Thick wall theory:

$$\sigma_r = C_1 + \frac{C_2}{r^2}$$

$$\sigma_h = C_1 - \frac{C_2}{r^2}$$

Boundary conditions:

@ $r_3 = 0.548 \text{ mm}; \sigma_r = 0 \text{ MPa}$

@ $r_2 = 0.540 \text{ mm}; \sigma_r = -2.31 \text{ MPa}$

So,

$$0 = C_1 + \frac{C_2}{(0.548)^2}$$

$$C_1 = - \frac{C_2}{(0.3)}$$

And,
\[-2.31 = C_1 + C_2/(0.540)^2\]
\[-2.31 = - C_2/(0.3) + C_2/(0.292)\]
\[-2.31 = C_2(0.0913)\]
\[C_2 = -25.29 \text{ MPa}\]
\[C_1 = 84.32 \text{ MPa}\]

Therefore, the equations for my principal stress are as follows:

\[\sigma_r = 84.32 + (-25.29)/r^2\]
\[\sigma_h = 84.32 - (-25.29)/r^2\]

Therefore, the maximum and minimum principal stress on the outer surface of the kiln (\(r = 0.548 \text{ mm}\)) is equal to:

\[\sigma_r = 84.32 + (-25.29)/(0.548)^2\]
\[\sigma_r = 105.34 \text{ kPa}\]
\[\sigma_h = 84.32 - (-25.29)/(0.548)^2\]
\[\sigma_h = 168.53 \text{ MPa}\]

Maximum principal stress = \(\sigma_1 = 168.53 \text{ MPa}\)
Minimum principal stress = \(\sigma_2 = 105.34 \text{ kPa}\)