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Static structure analysis of 5000tpd Rotary cement kiln using ANSYS Mechanical APDL

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Abstract

Rotary cement kiln is regarded as the heart of cement manufacture in any cement plant widely used to convert raw material into clinker. The capacity of a plant is determined by the production in the kiln whose sizes can be very large to handle higher production capacities of as much as 10000 tonnes per day (tpd) of raw meal to be processed. The ultimate cement quality is determined at the kiln. The varied physical process operations occurring and the equipment's complex construction with required strength necessitates in-depth analysis of static structural aspects for optimized efficiency in performance.

In this paper, a 5m diameter 72m length kiln is designed in Pro-E to determined structural total weight being an assembly of components. Its then modeled and analyzed in ANSYS using Mechanical apdl being a statically indeterminate system where kiln stresses distribution status on the cylinder shell is difficult to obtain through general analytical solution methods. Following the analyzed results, a relevant conclusion is given where the analysis results would be useful in design of rotary kiln cylinder optimization for excellent performance and scholarly work.

Keywords; Rotary kiln, Finite element analysis, von-mises stress, tyre.

1.0 Introduction.

Cement can be regarded as a finely ground, non-metallic, inorganic powder which when mixed with water forms a paste that sets and hardens. It is a basic material for building and civil engineering construction(Kohlhaas B. et al, 1983). The hydraulic hardening is as a result of calcium silicate hydrates or aluminate hydrates incase of aluminous cements formation resulting from the process reaction between water and the cement constituents mixture.

As shown in Figure 1, Rotary kiln is a requisite complex equipment used in many processes requiring raise of temperature through a continuous process. These processes include drying, heating, stirring and mixing. The most common and industrial major applications of rotary kilns is in cement production. Because of their flexibility, rotary kilns are also used in incineration of waste materials, mineral processing, chemical and lime production et cetera.

The wide applications of rotary kilns can be attributed to factors which include the capacity to handle varied feed with different particle size and the ability to maintain discrete conditions in any operating environment. However, despite these vital factors, there are some typical problems that affect kiln operations for instance low thermal efficiency, low product quality and dust generation. Thus if not taken keen interest into, there would be many losses as the equipment status due to frequent breakdown detrimental to efficiency and expensive maintenance costs.

To achieve clinker product with the desired quality there is a considerable need to study and analyze design parameter aspects of the kiln. It is this quality of the clinker that determines the ultimate strength of cement in the building industry. This means that if the quality is compromised from the production of raw material processes i.e. in the kiln, it would be translated to poor infrastructure development. Therefore, to achieve the desired quality it is necessary to gain more insight on the static structural analysis phenomena of the kiln.

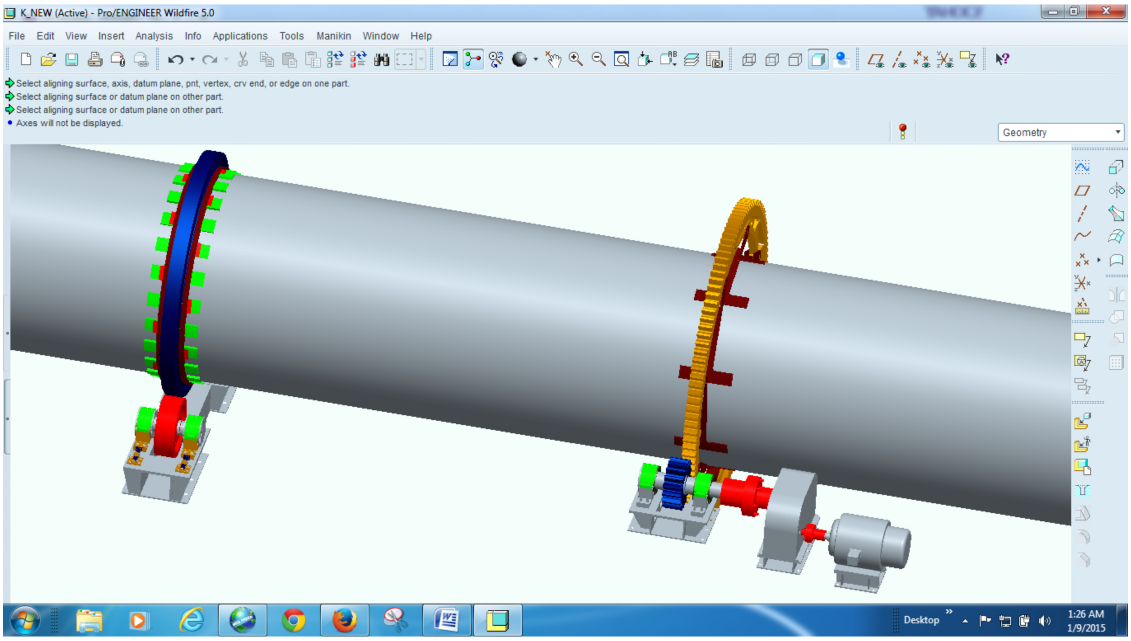

Figure 1:Section of Rotary Cement kiln on Pro-E graphics window.(*Jan 2015*)

1.1 Rotary kiln role in cement Production process.

In cement production, rotary kilns are widely used to convert raw materials (raw meal) into cement clinker. Cement production is a combined physical and chemical process highly energy intensive which involves the change of raw material into cement for application into highly binding strength supporting structures and other infrastructural works. Once raw meal is turned to clinker from kiln, it is then ground in a mill to produce cement. Basically, production of cement follows a series of standard steps from the mostly used Portland cement to all other types. It is obtained from decomposition (by heat) of Limestone (calcium carbonate, $CaCO_3$) to obtain calcium in a calcination process i.e. $CaCO_3 \rightarrow Cao + CO_2$. The calcium oxide from calcinations combines with silica, alumina, Iron oxide, ferrous oxide to form the silicates, aluminates and ferrites of calcium at very high temperatures typically 1300-1500°C in the kiln in a process called clinkerization to produce clinker (The Cement and Concrete Association of NewZealand, 1989)

1.1.1 Clinker Description.

Clinker composition is made up of four basic substances which include; Cao, SiO_2, Al_2O_3 and Fe_2O_3 combined into four minerals after physical and chemical reactions to form C_3S, C_3A, C_4AF and C_2S. From conversion of raw material into clinker, there are 4-stages involving chemical and physical change.

Stage I: Destruction of compounds.

This can also be regarded as evaporation and pre-heating. A mixture of limestone ($CaCO_3$) and clay is mixed in certain percentages, the mixture is then burned in a reaction. All the reactants in the process are set for a combination. Water is evaporated at 100°C, chemical combined water at 250°C – 450°C, decomposition of $MgCO_3$ takes place at 450°C – 620°C and that of $CaCO_3$ at 820°C to form oxides which take part in a later re-combination process.

Stage II: Transition stage.

This can be regarded to as calcining stage. The process takes place at temperatures 900°C – 1200°C which involve appearance of liquid necessary for cementation. Heating of materials continue and Na_2O, K_2O alkalis, MgO are melted. The melt liquid help in generating transit compounds which include; C, S, F and A. As the temperature increases, transit compounds and CaO increase gradually upon attaining temperature of 1100°C. Also C, C_3A and C_4AF appear.

At 1338°C – 1420°C the latter two minerals begin to melt marking the liquid phase appearance hence the generation of C_2S is ended and starts to transform to C_3S, calcium silicate (clinker) which determines the strength of cement. In the combustion process, liquid phase is maintained at 25% so as to avoid over-cementation and ball generation which may damage the kiln.

Stage III: Cementation.
This is a crucial stage which takes place at temperatures 1338°C – 1420°C. It involves generation of C_2S which then combine with single carbons to form C_3S. When the entire single C is combined, the cementation process is ended. The process is a highly endothermic reaction in which it has been found that to produce one kg of calcium silicate crystals (cement clinker), 110 kilo-calorie heat quantity is released.

Stage IV: Cooling.
The molten cement clinker produced is cooled as rapidly as possible to ensure its stabilization. The process takes place at temperatures 1420°C – 100°C. The process is rapid to ensure C_2S crystal phase transformation to C_3S does not decompose back into C_2S and no crystallization of MgO. Slow settling and hardening speed of crystallized MgO would result in later greater cement concrete expansion. The ambient air used to cool the clinker is fed into the kiln as combustion air to ensure no losses in energy by utilizing the heat produced.
The table 1 below gives a summary of the major composition of Portland cement after chemical reactions to produce cement materials:

Table 1: Mineral composition of Portland cement (The Cement and Concrete Association of NewZealand, 1989)

Clinker Compound	Abbreviation	Chemical formulae	Typical concentration (%)
Tricalcium silicate	C_3S	$3CaOSiO_2$	60 - 70
Dicalcium silicate	C_2S	$2CaOSiO_2$	10 - 20
Tricalcium aluminate	C_3A	$3CaOAl_2O_3$	5 - 10
Tetracalcium alumino-ferrate	C_4AF	$4CaOAl_2O_3Fe_2O_3$	3 - 8

2.0 Basic theoretical knowledge of the Rotary Kiln.
Cement Rotary Kiln is a cylindrical vessel made of rolled steel plate, welded together to form a cylinder whose installation is slightly inclined to 2-4% to the horizontal to enhance movement of material as the cylinder rotates along its axis. Research has shown that pyro-processing in the kiln consumes 99% of the total energy supplied hence the most energy intensive step during the cement manufacture process(Kohlhaas B. et al, 1983)(Kaustubh S.M, Vivek V.R, 2008).

In addition, the strength development of the cements is strongly dependent upon calcinations conditions, principally temperature which is dependent on kiln conditions(Boateng A.A, Barr P.V, 1996). Different conditions on the rotary kiln have been modeled using different methods which include Monte Carlo method for radiation, three moment mechanics equation, the moment distribution method, finite volume code for energy equations in the kiln walls and energy conservation equations involving chemical reactions for the clinker. Essentially, modern kilns have a diameter 6m and up to 100m length. Any larger kiln would bend too much under its own weight leading to cracks on the refractory material.
The equipment has gradually been developing to meet performance needs right since its invention in Leblanc process as a continuous reactor in the mid 19th Century(European Commission, December 2001) to the current research on further designs undertaken and some kilns are produced as long as 150m long continuously producing over 15million tonnes of cement per year, operating at temperatures up to 1500°C.

Depending on the operating conditions, generalized suggestions by different designer manufacturers have been put across on considerations which include;

- **i.** Definition of the process or desired reactions.
- **ii.** Thermal analysis involving moisture and heat transfer.
- **iii.** Chemical analysis of materials for a desirable reaction atmosphere.
- **iv.** Sizing of capacity and amount of heat required or generated in the kiln.
- **v.** Mode of firing direct versus indirect.
- **vi.** Refractory materials to be used on kiln internal lining.

Being the core equipment in cement manufacture, thermal and mechanical status of cylinder shell analysis would be crucial in any engineering application because of its sensitive damage and costly maintenance. Originally, the shells being a flat plate with a particular form of three dimensional solid presents no theoretical difficulties in case of elasticity. However, the thickness of such a structure is much smaller compared with other dimensions and a complete three dimensional numerical treatment is not only costly but in addition often leads to serious numerical ill-conditioning problems of deformation, lateral displacement etc(Zienkiewicz O.C, R.L Taylor, 2009). The rotary cylinder should possess sufficient stiffness and strength to withstand any adverse operating conditions of both static and thermal effects. Any malfunction would be as a result of severe bending deformation during production which can lead to radial deformation hence affecting the equipment's construction on its refractory cracking or making it loose.

In the design and installation of kilns, the structure is basically a statically determined beam system where the support load is always known or statically indeterminate where the support load cannot be determined using direct structural mechanic equations such as Macaulay's method. The length to diameter ratio is of much consideration as it ensures a reduced gas velocity and the dust recirculation, In addition to securing a thermal load lower burning zone. Also it has smaller size requirements and reduced surface heat loss(FLsmith, 2011). Different design values for manufacturing rotary kilns have been proposed on different papers and a typical example by *FLsmith* design manual is represented graphically in figure 2. Rotary kilns equipped with pre-heaters have a typical Length to Diameter ratio (L/D) of between 10:1 to 17:1(European Commission, December 2001)(Feeco international rotary Kiln design).
However the largest long rotary kilns have a length to diameter ratio of up to 38:1 and can be more than 200meteres long. These are designed for drying, pre-heating, calcining and sintering, so as it's only the feed system and cooler which have to be added.

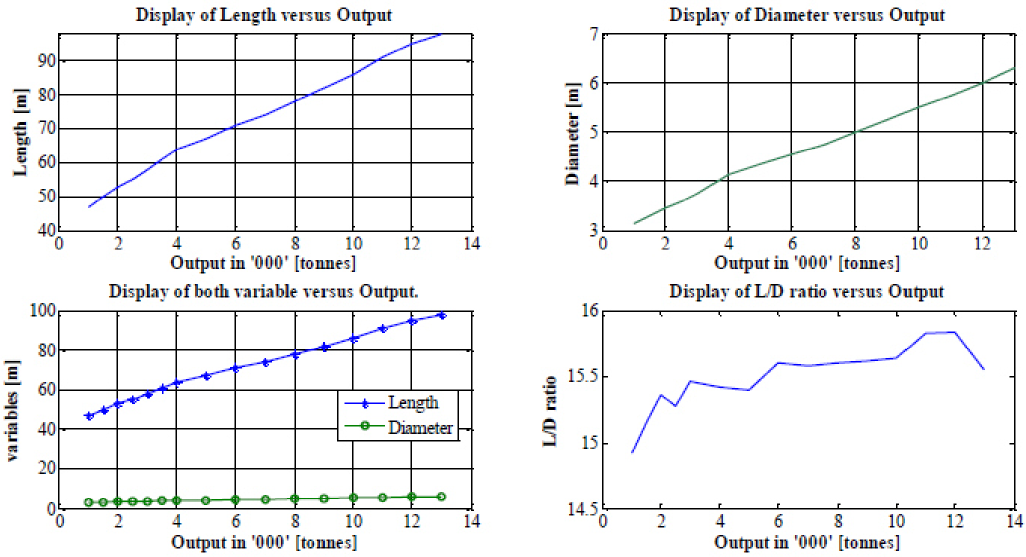

Figure 2: Data guidelines for standard cement kiln design dimensions with corresponding output from design data.

2.1 Static Analysis Theory.

Static structural analysis is considered as probably the most common application of the finite element method. It involves both linear and non-linear analysis. The analysis determines the displacement, stresses, strains and forces in the structure under static loading conditions that do not induce inertia and damping effects. During this type of analysis, the quantities are derived from nodal displacements. Static analysis calculates the effects of steady loading conditions and for instance such a rotary kiln it would include steady inertia loads i.e. gravity and rotational velocity.
Since the Rotary kiln structure is long, a statically indeterminate system i.e. with multi-supports is applied, it would not be easy to develop a rigorous solution using routine approaches. Li Xue et al gives a general model for statically indeterminate beams with varying flexural rigidity (Li Xue-Jun, Xu Ping-Yu, Liu Yi-Lun , 2003).
In the design and determination of structural strength, deformation, bending, displacement and general stress distribution ought to be accurately determined. To analyze the whole system complicated by rotation, matrix model methods are developed putting into consideration equivalent stiffness for the system sections (Afshin T., Mohammad B., M.T Ahmadian, 2012).
In cylindrical systems, the stress and strain vector in its coordinate system is defined according to equations 1 and 2 respectively (Cui Deyu, Xu Yuanming, 2012)(Weigang Z, ZhongZhihua, 2008).

$$\sigma=[\sigma_r\ \sigma_\alpha\ \sigma_z\ \tau_{r\alpha}\ \tau_{zr}\ \tau_{\alpha z}]^T \quad \ldots\ldots\ldots\ldots(1)$$

$$\varepsilon=[\varepsilon_r\ \varepsilon_\alpha\ \varepsilon_z\ \gamma_{r\alpha}\ \gamma_{zr}\ \gamma_{\alpha z}]^T \quad \ldots\ldots\ldots\ldots(2)$$

where **r, α, z** are cylindrical coordinate determining the element position vector in radial, tangential and axial

coordinates respectively;
and **σ, τ, ε, γ** are normal, shear stresses and normal, shear strains respectively. Considering the general global stiffness matrix; $\sum_i K_e^{(i)}$

Their corresponding Finite element stiffness matrix is given in [3].

$$K_e = \int_{V_e} B^T BdV \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad \ldots\ldots(3)$$

Which reduces to [4] for a constant thickness cylinder such as kiln cylinder section shell segment.

$$K_e = B^T EBt\Delta = B^T St\Delta \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

In an analysis based on continuous beam model, the support and friction loads are determined to provide boundary value conditions in finite element analysis. The refractory layer should be assigned a smaller parameter elastic module so that the stiffness effect is much reduced.
Wang H. et al on the analysis of a barrel length of 50.95m and 2.75m diameter having three supports concludes that the rotary torque and friction have little effect on the stress and deformation of the shell; and secondly, the maximum equivalent stress and the worst ovality of the cross-section are at the same location close to the 2nd kiln tyre (Wang H, Xie K., Chen Y., Wang D. , 2010).

3.0 Finite element Analysis.

3.1 Model Description.

The kiln model with 5m diameter and 72m long made of mild steel with varied shell thickness; Inclination 3.5%; Total weight 660tonnes. The installation support positions are as shown in table 2 below.

Table 2: Distances between supports.

Supports	Distance(mm)
Feed end – I	10000(±3.0)
I – Girth	4000(±2.0)
I – II	29000(±7.25)
II – III	27000(±6.75)
III – Discharge end	6000(±1.8)

3.2 Choice of Finite element elements.

For the accuracy of results, choice of right materials is vital. Most components, parts or systems can be modeled as beams, plates or ax-symmetric elements. The cement kiln equipment assembly possess different detachable units which cannot be analyzed directly into ANSYS database without erroneous results and the program's capability. In addition, a thorough understanding of strength of materials is a pre-requisite on choice of elements. Also, the kind of loading and boundary conditions applied on the analysis determines the type of element to use.

3.2.1 Structural ANSYS Solid elements.

SOLID45: The kiln equipment has been modeled using structural element SOLID45. This is a three-dimensional brick element used to model isotropic solid problems. It has eight nodes, each with three translational degrees DOF in the nodal x, y and z-directions. The element may be used to analyze large deflections, large strain, plasticity and creep problems. The solution output consists of nodal displacement components of stresses in x, y and z-directions; shear stresses and principal stresses. The elements stress directions are parallel to the element's coordinate systems.

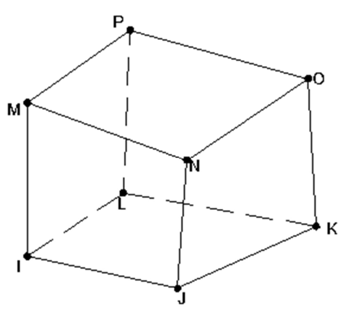

Figure 3:The solid45 element used by ANSYS

3.3 Finite element static structural analysis.

3.3.1 Geometrical modeling in ANSYS.

The kiln geometric model is as described in chapter three with the specific key parts and geometric features. The 3D model in ANSYS is as shown in figure 4 with supports I,II,III and girth gear IV each installed as per table 2.

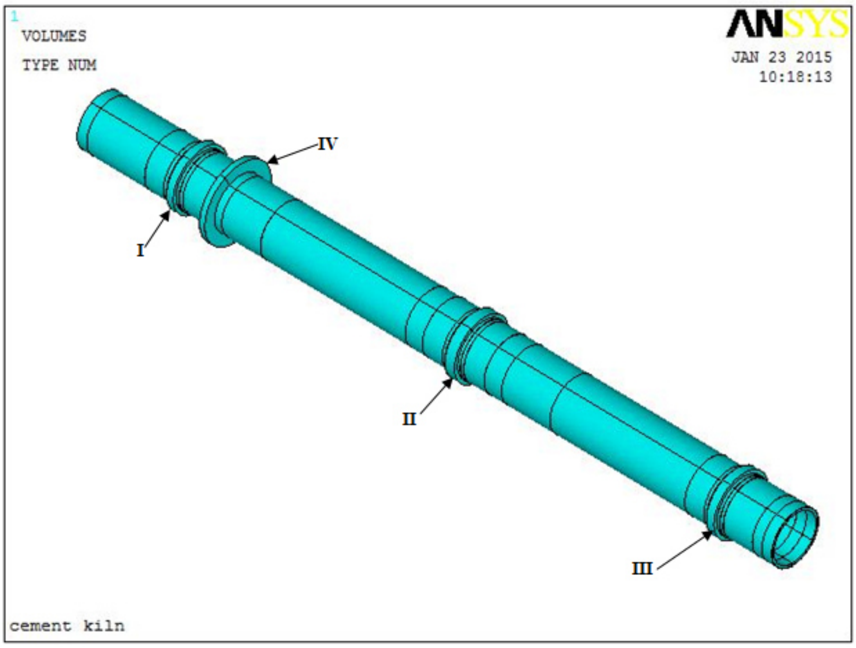

Figure 4: 3D kiln model in ANSYS window

3.3.2 Meshing.

For static structural analysis, the model geometry, nodes and the coordinate system are as shown in figure 5 which supports both free and mapped meshing quadrilateral element shapes. However, the model can also be analyzed using SOLID186 a higher order version of SOLID45.

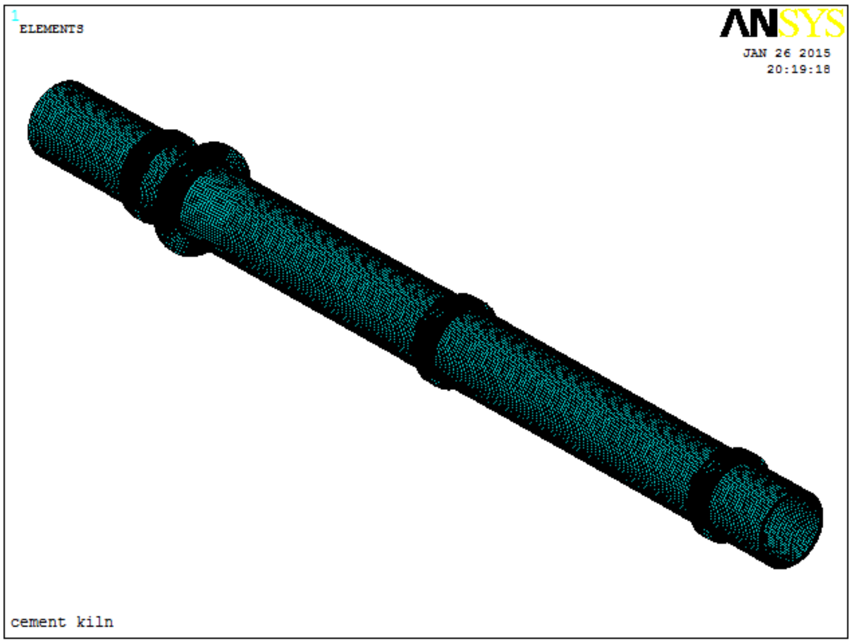

Figure 5: Meshed model.

3.3.3 Assigning Solution controls.

The model boundary conditions and constraints are set to generate closely accurate results due to the complexity of the kiln structure comprising different parts modeled as a simplified unit structure. The design in Pro-E generated the weights of single unit as per the properties of the parent materials before assembly. The components include; refractory, girth gear, belting leather and supports rings. Due to the girth gear design, it is modeled as a single ring unit to simplify the analysis.

The closely coincident and equivalent items are merged whereas higher numbered coincident items are deleted for identical elements which has no effect on the model's geometry but on topology only.

The analysis is basically static steady state hence constraints are established on nodes by displacements, rotations and pressure load. The loads applied include; cylinder component load, material load applied as surface pressure. The kiln cylinder inclination at a 3.5% (2°) to the horizontal is modeled by offsetting the working plane triad position relative to x, y, z planes.

It should be noted that the three support positions have the kiln positioned on rollers at 240° and 300° degrees span hence treated as displacement positions; DOF: ux, uy and rotations x, y, z.

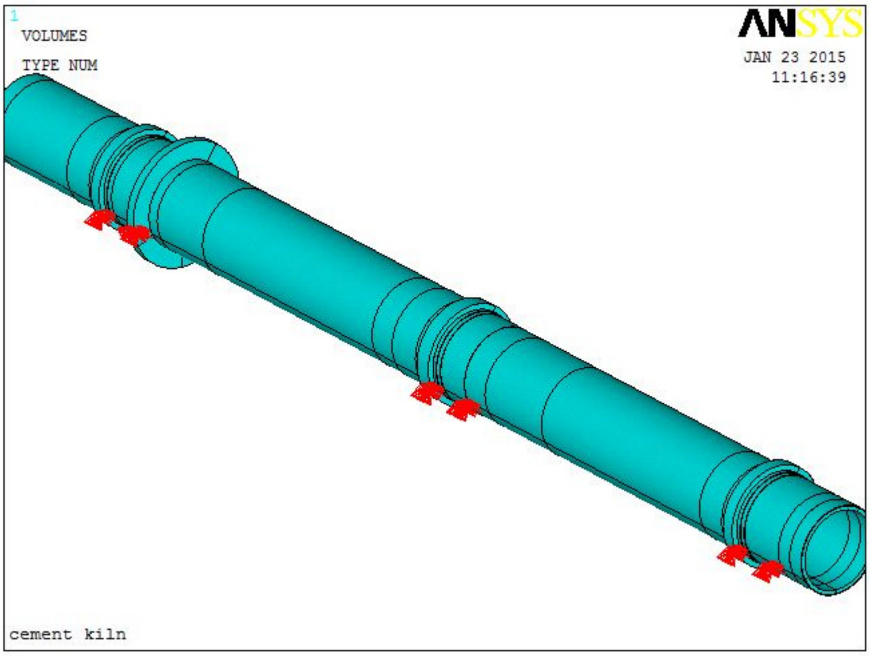

Figure 6: Bc's and constraints applied on the model.

3.4 Simulation results.

The simulation results stored in database are viewed by applying contour plots of the deformed model, listing, graphical illustration mapped onto paths to view each desired section. The results include stresses, deflection and reaction forces.

3.4.1 Stress distribution.

Stress analysis are performed to ensure the equipment does not fail due to stress levels exceeding the allowable values. Due to a combination of elements attached onto the main component and refractory, deflections should be considered as they are often more limiting than stresses. Excessive deflections would result to failure. Figure 7 shows principal stresses 1,2,3 and Von-mises stress general distribution on the deformed model in respective windows 1-4.

i) **Axial stress distribution.**
Different positions were considered under inner diameters and cylinder shell diameter respectively for L=72m at 0° and 90° component positions and stress curves are as shown in figures 8a,b.

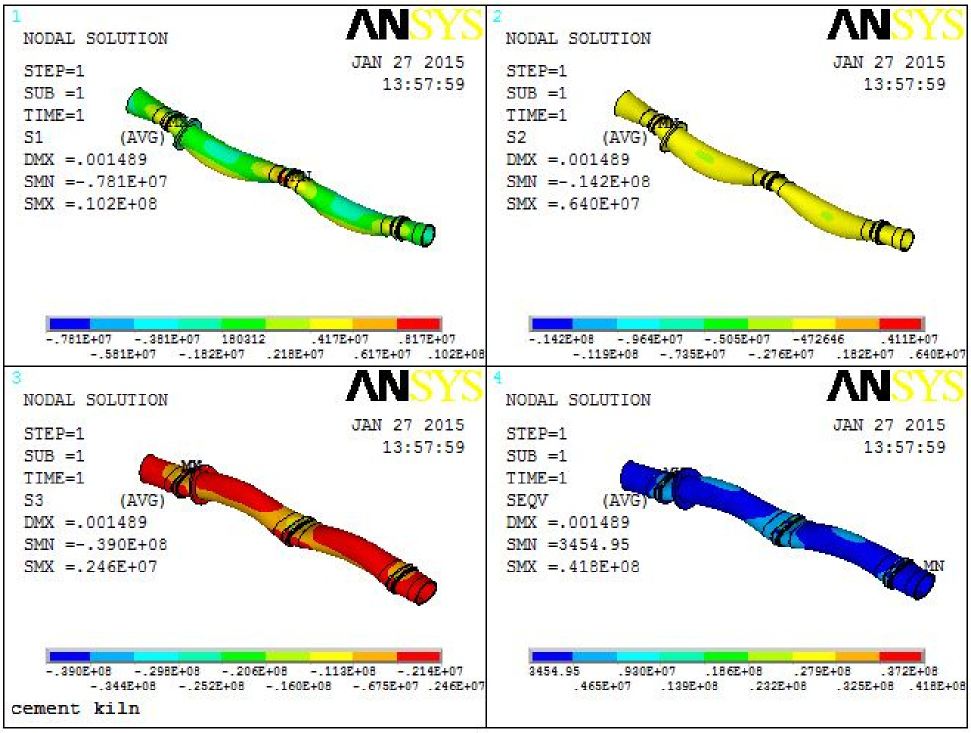

Figure 7: Stress components x, y, z and Von-mises

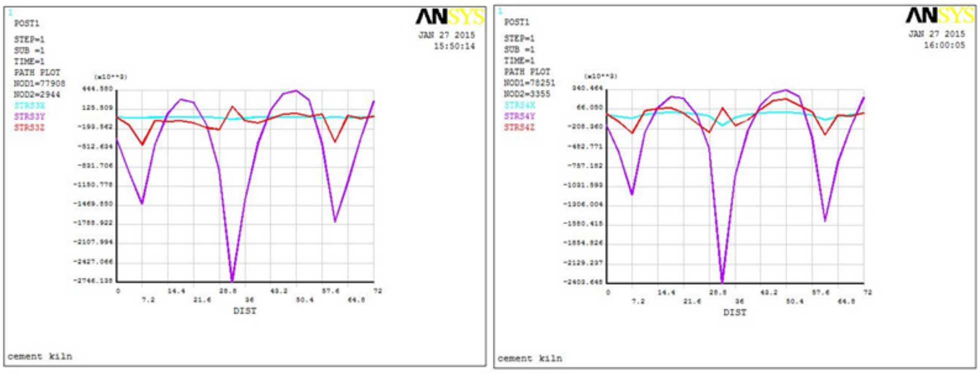

Figure 8: a) Principal stresses 1,2,3 and von-mises stress axially.

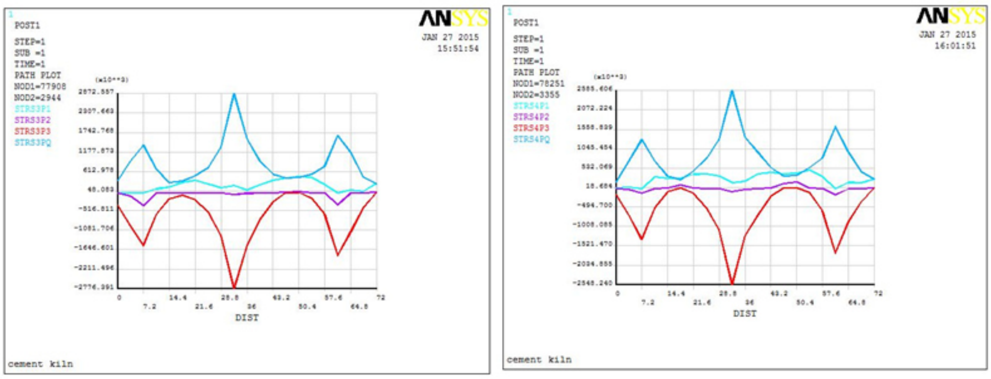

Figure 8: b) x,y,z components of stress.

3.4.2 Displacement Results

The nodal displacement curves; ux, uy, uz, usum results are shown in figure 9 below with the respective positions.

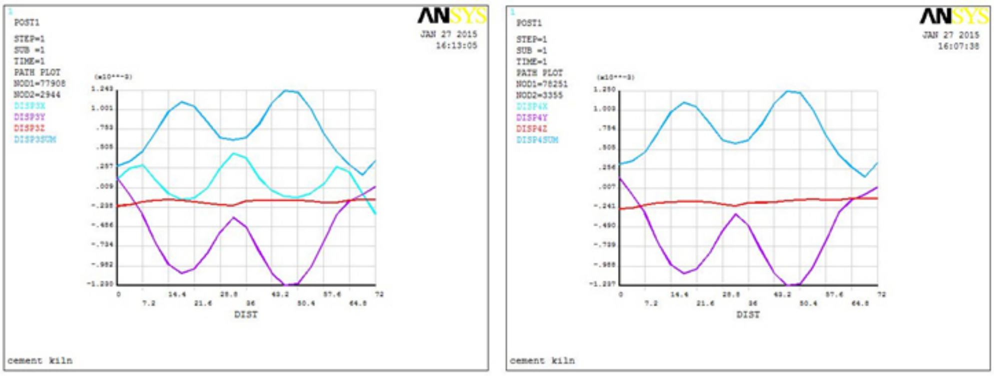

Figure 9: Nodal displacement positions.

3.5 Discussion of Results.

Figures 7 and 8 illustrate stress contour and curves along the kiln body respectively. It can be noted that the maximum von-mises stress occurs between the supports which agrees with the theoretically expected trend. The kiln cylinder equipment experiences both tensile and compressive stress load with the latter maximum along the y-direction. This is a clear indication due to the equipment components and installation.
However, in both cases stress is concentrated around the support positions with second support position bearing the maximum stress.
The stress values are much less than the material yield strength hence within the safe working limits. It should be noted that since the kiln equipment is always under continuous use experiencing rotations with raw material load and inclined, the stress distribution is no longer uniform hence minimal gradual failure. This axial and radial movement with load contributes to pitting at the tyre positions with time. For a radial case consideration, the stress distribution would follow a similar trend due to symmetry. However, in a practical situation due to loading this may not be exactly the same.

As shown in displacement curves figure 9 the maximum deflection occurs between 2nd and 3rd supports with a value 1.489mm along y-direction. This it should be noted that the whole cylinder thickness is not uniform hence portrays a dynamic behavior than targeted. Depending on the material pressure load and velocity, the value practically change. The results outcome therefore are in agreement with the existing conditions. Also the maximum deflection value is safe hence cannot result to buckling thus safe working of the equipment.

4.0 Conclusion and suggestions.

The analysis of a full kiln model has been done. The results obtained are reasonable and reflect trend both researched, experimentally documented, theoretically engineering judgement and from experience. The analysis has an upper advantage with regard to considered FEA models due to a full 3D physical model which made the results reflect the actual predicted outcome. The model results display guide would be much significant to the industry especially to situations involving design engineers and operators. The model has clearly illustrated the significance of materials data, properties such as section thicknesses, variations in technical design parameters and non-linear effects.

As per the analysis and discussion the results can be applied in materials selection for the cylinder rotary area part to model on gradient and thickness. The stress concentration locations can be modeled using a thicker plate alternately for all sections to ensure that there is convergence in rigidity for the entire equipment. The stresses further are influenced on the heating effects as the kiln equipment is under continuous high temperature heating.

Due to differences in barrel plate section thickness welded together, the welding chamfer reduces the plate thickness hence a change in connection position resulting to stress concentration around the joints. For the refractory due to large ovality of the support sections, second support has greatest shell thickness with a higher outer diameter to ensure minimal ellipticity. This ensures that the equipment is easily manufactured in accordance to standard engineering practices.
Further study suggested on;

- study on the various filling degrees with varied design parameters.
- dynamic analysis on the full kiln model. Since the rotary kiln processes are characterized by large inertia, non-linearities, time-dependent variables and multi-disturbances as the shell body rotates during production. The analysis would provide a clear actual overview of the equipment.

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