to Ovality, it would most likely occur first at the riding rings where Ovality is the greatest[Idem 1996]. Failure modes that can be associated with high Ovality include[Idem 1996]:
1-Prematuremechanicalrefractoryfailure.
2- Overheating and /or failure of carrying mechanism bearings.
3-Shell cracking.
4- Weld cracking.
The kiln Ovality plays an important role in determining refractory life , no correlation, however, has been developed between refractory wear rate and kiln Ovality.Cement rotary kiln refractories are worn by the synergistic effect of thermal, chemical and mechanical stresses. These stresses are complicated and it is quite difficult to distinguish the wearing causes in actual conditions. In this research only mechanical stresses caused by Ovalities have been considered.
The graphics data [Tuchiya 1996] (Figure 1) clearly illustrates an increased brick wear rate with increased Ovality

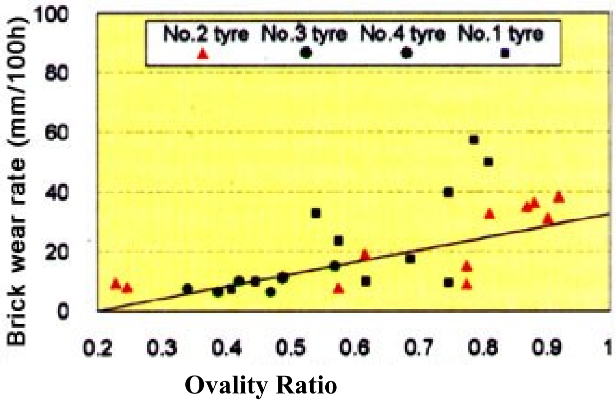


Fig 1: Brick wear ratio vs. Ovality

The Economic Side

Total refractories production in United States in 1998 was 3.66 million metric tons with a value of $2.379 billion Refractory sales are expected to reach $3.2 billion by 2010 [Semler 2000].About 20% of productions are consumed in the cement industry [Semler 2000] .Figure 2 show the cost of production vs. year, This figure demonstrate that significant amounts of refractories are produced and consumed.

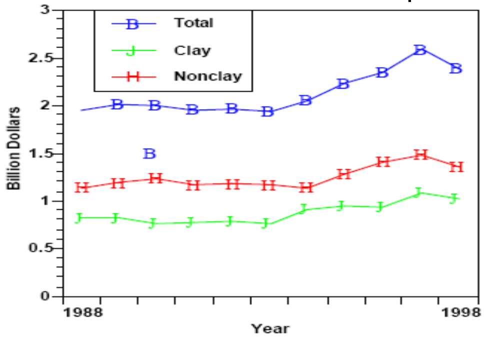


Figure 2. Value of Shipment of Refractories in USA (Source: US Census Bureau, March 2000).

For example Kufa cement factory consume about 200,000 alumina brick every 8-10 months and about 50,000 Magnesite brick every 12-14 months for each kiln (about 20-25% of brick damage is due to Ovality [Department of kilns ,Kufa cement plant].

The total cost of replaced brick is about 700-750 thousand $ for each kiln by year. So the failure of refractory lining in cement kiln is expensive, not only the cost of refractory replacement but also the lost in production time. Re-lining a kiln requires that the system be completely shut down, and under the best circumstances take about 12 days for a partial rebuild ,longer for complete rebuild. A rebuild involves cool down up to 6 days and teardown and repairs 5 days for a partial rebuild and 7-10 days or longer for a full rebuild[Department of kilns ,Kufa cement plant]. Figure 3 shows the damages occur in bricks due to Ovality while Figure 4 show the refractory rebuilding in Kufa cement kilns.

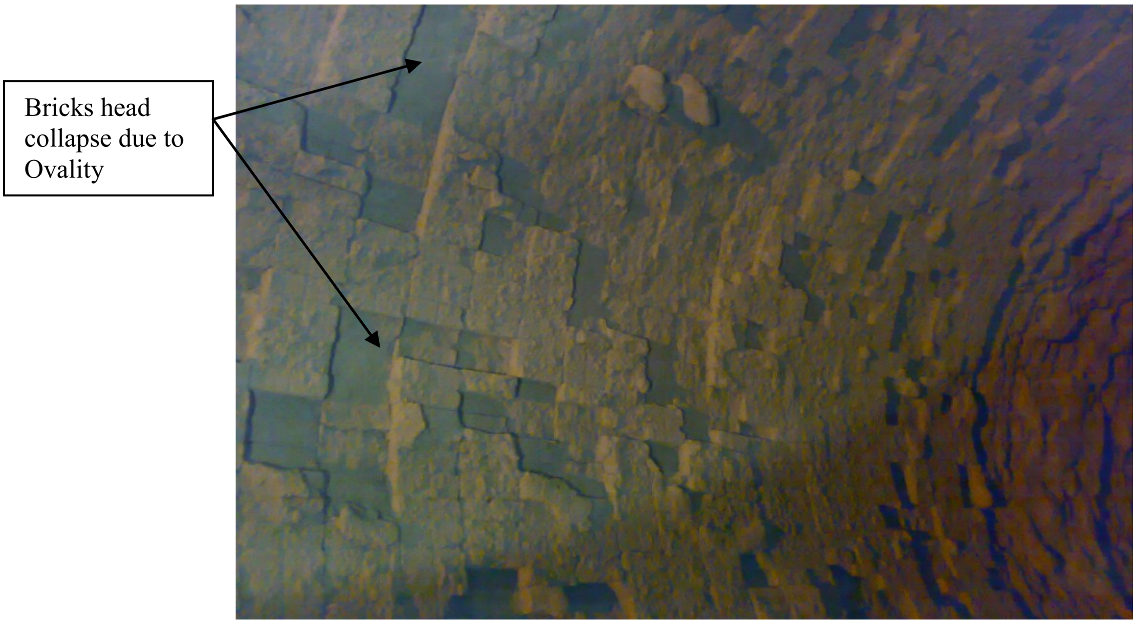


Fig 3 : Damage of refractory bricks due to Ovality (about 3 months of kiln operation ,Kufa cement plant, kiln No.2,tire base No.2) about 20% of brick thickness is fall down.

Fig 4 :Refractory Brick Re-building at Kufa Cement Factory (Kiln No.2).

Problem Statement

Refractory bricks lining cement kilns exposed to damages due to Ovality phenomena, this damage may be in turn caused kiln shell corrosion and the cost will be as much as higher than anticipated.

The costs of lining corrosion include:

1. Kiln downtime.
2. Removing the damaged lining.
3. Cost of new, replacement brick lining.
4. Reduced production (about 1000-1400 tone of clinker / day)..
5. Safety hazards

Research Purpose

The main purpose of this research is to Numerically determine the damage occur in lining brick due to Ovality and also make recommendations in order to reduce the Ovality Phenomena and cement plants losses.

Research Objectives

1-Explanation of mechanical damage of the kiln shell and refractory bricks due to Ovality.

2-Studying the damage factors and cement kiln operation conditions.

3-Controlling the cement kiln operation conditions in order to reduces the damages of bricks and also the losses of cement factories due to Ovality.

4-Using a numerical method (Finite Element ,stress analysis) by special software Pro-Engineer to find out distortion due to the Ovality phenomena, and make a comparison with the practical results.

Literature Review

Phillips E.R 1998 , Studied the effect of kiln shell deformations on the lining bricks, he concern on the alignment of the kiln and he found that an ideal hot kiln alignment involves not only the horizontal and vertical axes of the shell, but the balance of the axial thrust of the kiln as well. When tires and support rollers are worn on the contact surfaces, making roller adjustments and training for axial thrust become delicate procedures.

Walter M 2008, studied Ovality of the kiln shell during rotation, he found that this deformation have a very effect on the mechanical stability of refractory. He used The Ovality beam, or 'Shell Test' rig, to measure the degree of flexing a shell undergoes during normal operation. He found that Ovality not only causing refractories damage but also lead to misalignment for kiln shell, and even shell cracks.

Goerge 2008 , He defined the dynamic Ovality as the degree of deformation of the kiln shell and determines the distribution of the cyclic, circumferential bending stresses in the kiln shell. He found that excessive Ovality can result in circumferential bending fatigue in the kiln shell and refractory lining failures. he calculated the Ovality on the basis of the tire migration and the Shell test method.

(Ahmed M. et al. 2011) concentrated on the analysis of stresses which generated on bearing of the carrying rollers of the rotary kiln in new Hammam Al-Alil factory. In addition the effect of misalignment is shown on stresses distribution and it's concentration. They used "(ANSYS 9.0)", based on finite element technique. They found that it was very efficient and accurate tool in stress analysis for many cases. The stresses had been calculated for the assumed cases. They found from results showed that the stress distribution and concentration on the bearing was altered with misalignment for each case

2-Materials and Method of Work:

The most types of refractories used in Kufa cement kilns are Alumina and Magnesia bricks. Types of refractories used in Kufa cement plant were shown in Fig. 5 and the physical properties were shown in Table-1

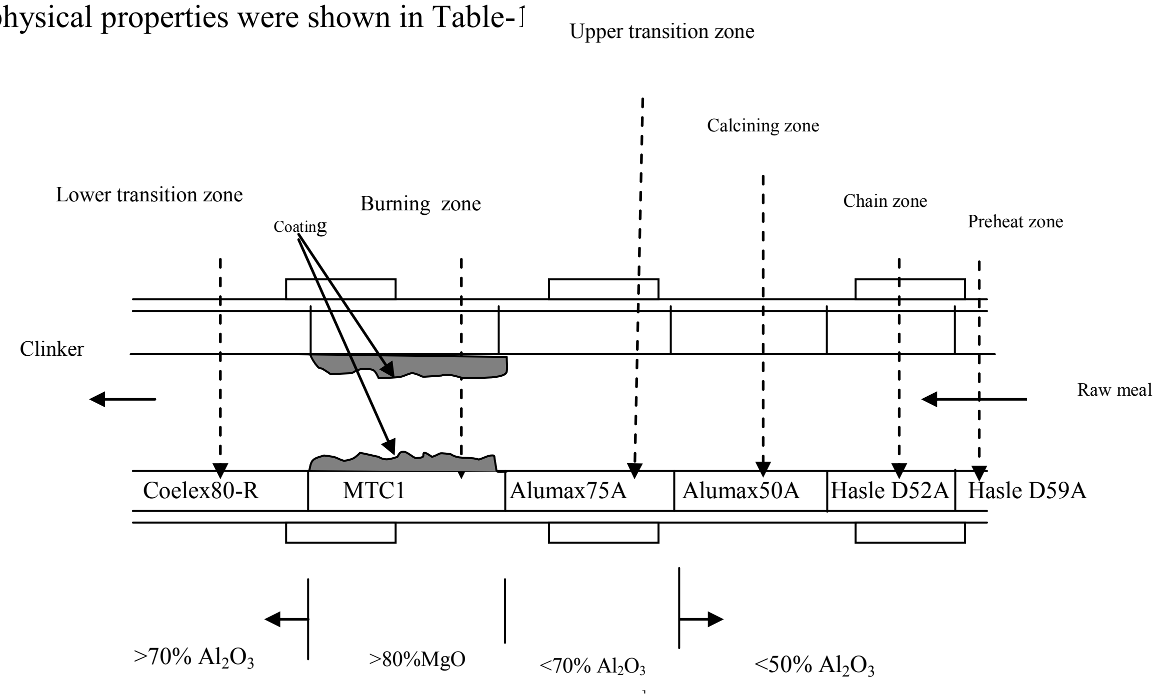


Fig. 5 : The cement kiln zones and temperature distribution (Operational Parameters:(Kufa Cement Factory) , Wet Production Method , Six Stages ,Radius (5.25-5.75)m , Length (175)m, (1.5-2.25) rpm.).[Kufa Cement Plant/Kilns Department)

Table -1: Physical properties of refractory bricks [Hasle 2007]

Physical Properties	**Coelex 80-R**	**MTC1**	**Alumax 75 A**	**Alumax 50 A**	**Hasle D59A**	**Hasle D52A**
Density (kg/m^3)	3100	3000	2700	2300	2500	2350
Apparent Porosity %	13.2	12	19	17	18	16
Thermal Conductivity (W/m.K) at 400ºC	4.12	5.11	1.66	1.13	1.4	1.28
Modulus of Elasticity (GPa)	109.4	128.3	25.7	34.9	32.3	41.4
(MOR) Modulus of Rupture (MPa)	17.5	17	12	14	18	16.5
Hot Modulus of Rupture (MPa)	16.7	16.2	10.2	11.3	15.6	14.2
coefficient of thermal expansion(α) $C^{-1} \times 10^{-6}$	12.1	11.23	8.8	8.3	7.7	7.5

Method:

Assumptions and Boundary conditions:

some assumptions was made to keep the structure as simple as possible and in the same time didn't affect the accuracy of the model. These assumption are:

- A 3-D finite element techniques was used to calculate the deformations in the kiln shell and the stress in the refractory bricks.
- The weight of cement kiln coatings was constant and taken from the kilns department tables (1700 Kg/m^3).
- The dimensions of refectory bricks was constant along the kiln length.
- Linear coefficients of thermal expansion (α) was constant .
- Materials densities (ρ) was constant.
- Total stress = $\sum$ (Elastic stresses +Thermal stresses).
- Elemental Equation was depended on minimizing the total potential energy of the system (E_p) which can be expressed as :

$$E_p = \frac{1}{2}\int_v [\sigma(t)]\varepsilon^T(t)dv - \int_v [\delta]^T \rho\, dv - \int_s [\delta]^T q ds \qquad (1)$$

ρ- the body force per unit volume. q- the applied surface traction, σ -stress, ε -strain, δ -displacement. Integration was taken over the volume V of the structure and loaded surface area, S .The first term on the right hand side of eqn (1) represent the internal strain energy and the 2nd and 3rd terms are respectively the work contributions of the body force and distributed surface load.

- The number of scanned shell temperature points taken for a complete rotation of the kiln was twenty five. The temperature of each calculation point through axial position was assumed an average mathematical value of all points.
- The shell temperature in any required point on the surface could be correlated by making an interpolation between the curve points of figures 8,9 as in the following Eqns.:

$$1^{st}\ 50\ m: \ T_{sh(1)}(z) = -0.0818\, z^4 + 2.3452\, z^4 - 17.628\, z^2 + 18.732\, z + 303.5 \qquad (2)$$

$$2^{nd}\ 50m: T_{sh(2)}(z) = -0.0723\, z^4 + 1.92\, z^4 - 16.594\, z^2 + 17.457\, z + 301.4 \qquad (3)$$

- The displacements of bricks was assumed restricted in the z-direction and equal to zero.
- Roller base ,tire and kiln shell were free toward the X-axis and restricted toward Y and Z-axis and have a moment of inertia toward Z-axis.
- The thermo-chemical effects (for example the infiltration of alkaline salts) on bricks cracking was ignored.
- The effects of kiln rotation was neglected as the speed was low (not exceeds 1.5 rpm).

Measurement of Creep and Tire Clearance (Ovality):

The technique for Rotary Kiln Ovality measurement, by Shell test apparatus, has been developed way back in the beginning of 1950's by G.Rosenblad[Geraldo 2002].Practically Ovality can be measured with a simple device shown in Figure 6. It consists of a pointer and a recording plate. The pointer is attached to the kiln shell by a magnet and pressed in contact with the recording plate which is secured with help of a magnet on to the tire. The creep "U" and the tire clearance "S" can be read directly from the plotted profile. Or the creep can be determined by suitably marking tire and the shell and then by measuring displacement between tire and shell.

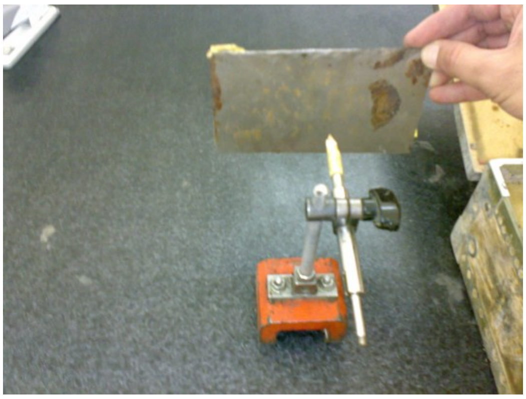


Fig 6 : The Ovality measuring device.

Theoretically Ovality will be simulated numerically in order to make comparison with practical side using software called (Pro-Engineer version 4) based on Finite Element Method , this done by enter all practical operational parameter(geometry, temperature, external load, gravity load, properties of materials and boundary conditions.)

The temperatures distribution of the kiln shell was measured practically by simple device called kiln shell scanner (Field located analyzer that measures the temperature of a kiln shell.) as shown in Figure 7, this device connected to computers in the control room using special software called (Data Temperature CS100).Figures 8,9 represent the first and Second 50 m of the kiln shell temperature distribution .This program measure the real temperatures of critical zones from 0 to 150 meters of kiln shell.

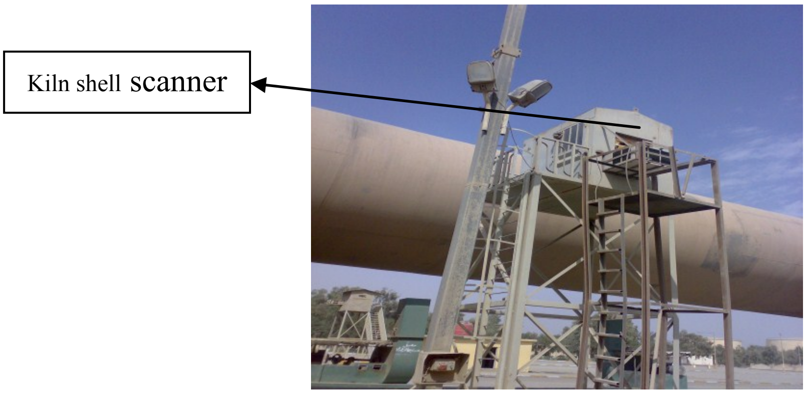


Fig 7: Kiln shell scanner

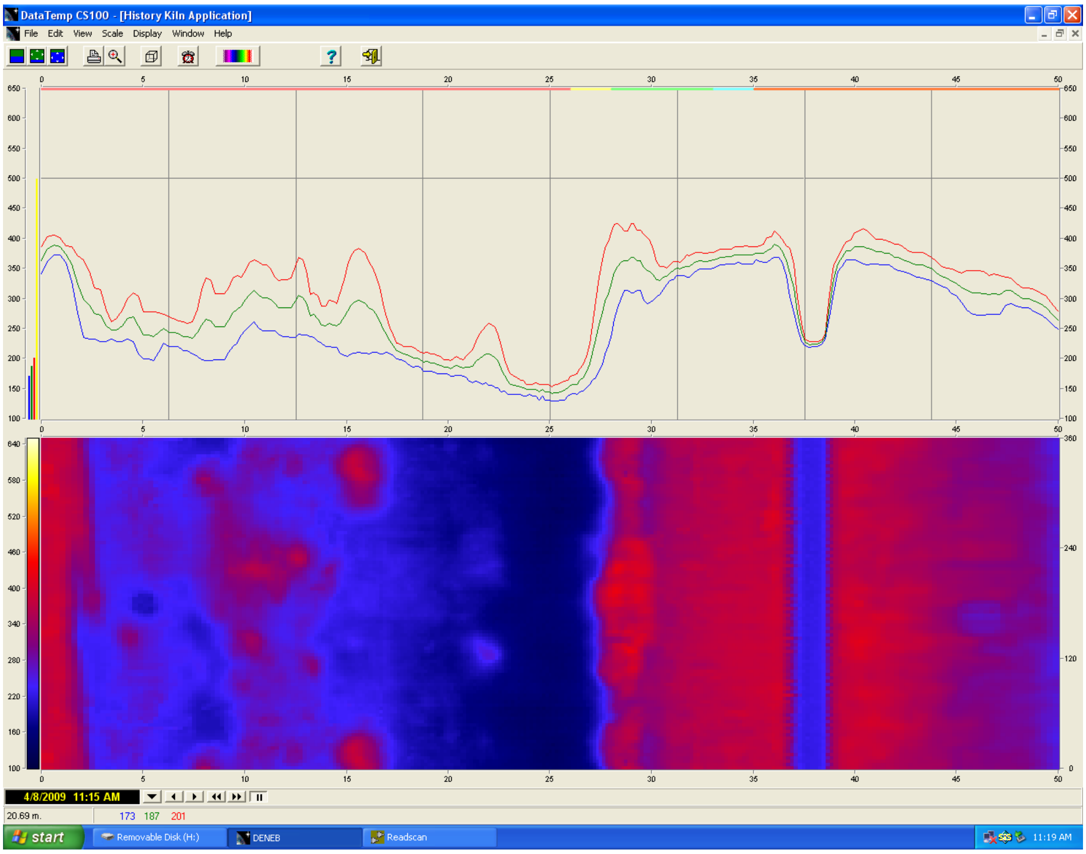


Fig 8 : The First 50 m of Kiln Shell Temperature distribution.

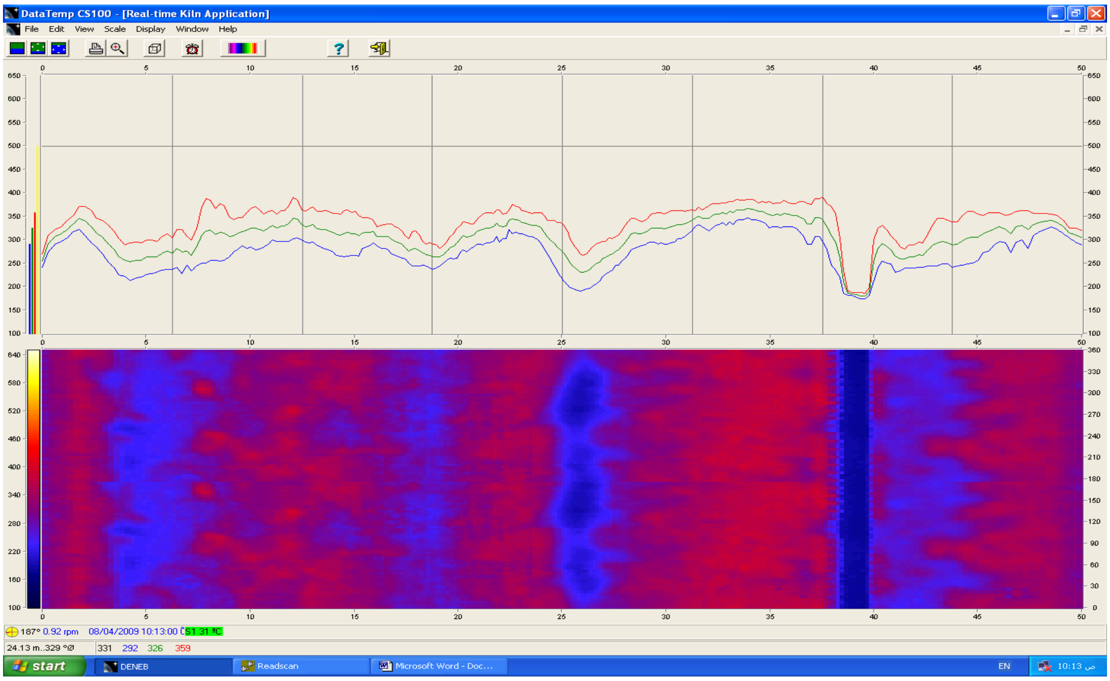


Fig 9 : The Second 50 m of Kiln Shell Temperature distribution.

3-Results and Discussion

The Ovality Data Input

The properties of kiln shell that required to be entered to the software Pro-Engineer in our solution are:[Kufa cement plant, kilns department)

Steel Shell , Isotropic

Density (ρ) = 7827 Kg/m^3, Elastic modulus (E) = 199.948 GPa, Poison^s Ratio (υ) = 0.27

Thermal conductivity (k) = 43 W/m.^{o}C, Linear coefficient of thermal expansion (α)=1.17e-05 C^{-1} , Kiln shell weight (w) = 4445.12 Kg/meter , Outer Diameter (d_1) = 5.2 m, Shell thickness (th_1) = 20 cm., Shell thickness at tires (th_2) = 22 cm ,Maximum shell temperature at burning zone (T_{max}) = 400 ^{o}C ,Minimum shell temperature (T_{min}) = 150 ^{o}C ,

Mesh-6537 solid element eight-node.

Refractory Bricks:

250 bricks for each ring shell (Alumina bricks),20 cm thickness, Isotropic.

200 bricks for each ring shell (Magnesia bricks), 22 cm thickness, Isotropic.

The physical properties of bricks were shown previously in Table 1 .

Mesh-8-node solid brick element.

The theoretical results from Pro-Engineer software was compare with practical results as in the following table:

Table 2 : The Ovality Test Results (Clearance between Tire and Shell)

Location (m)	Temperature ^{o}C	Ovality (cm) Pro-Engineer	Ovality (cm) Practical
Upper transition zone, tire base No.1 (at 45 m)	350^{o}C	12.9	14
Calcining zone ,tire base No.2 (at 90 m)	200^{o}C	3.4	4.2

It is shown that for both theoretical and practical the Ovality is large at base tire No.1 ,this may be due to the high temperature of kiln shell at this zone. Experimentally 7 cm and up is danger on brick lining[Tuchiya 1996] because this displacement is transfer into brick causing high stresses (more than the permission limit as mentioned previously in Table 1) and in turn these stresses will cause longitudinal cracks and so the collapse was occurred .

The types of elements and axis direction was shown in Fig. 10 and Fig.11.

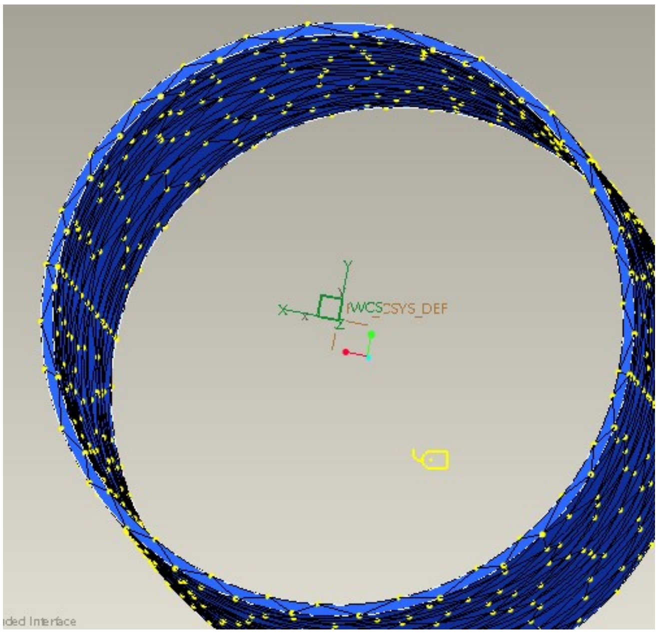
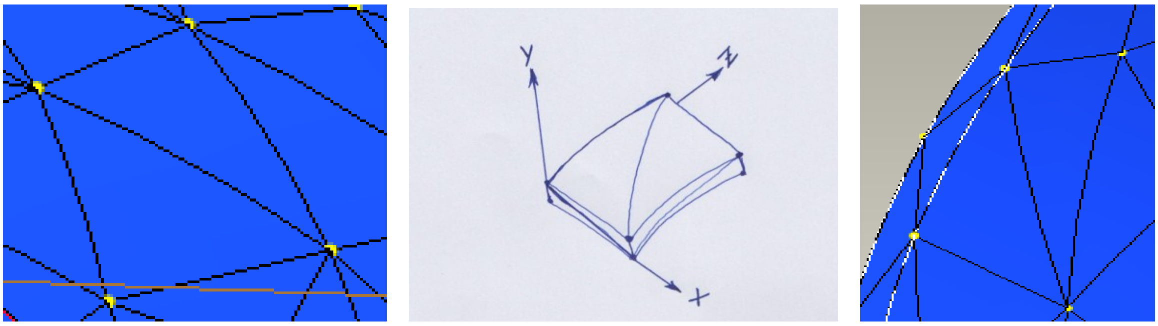


Fig 10: Mesh of 10 meter of Kiln Shell (6537 solid element eight-node) and the axis direction.



(a) (b) (c)

Fig 11: (a) 0.6 x 0.55 x0.5x0.45 m face and 0.2m thickness solid element 8-node.
(b) The direction of element axis.
(c) The element edge.

The results of kiln deformations from Pro-Engineer software are shown in Fig 12-14:

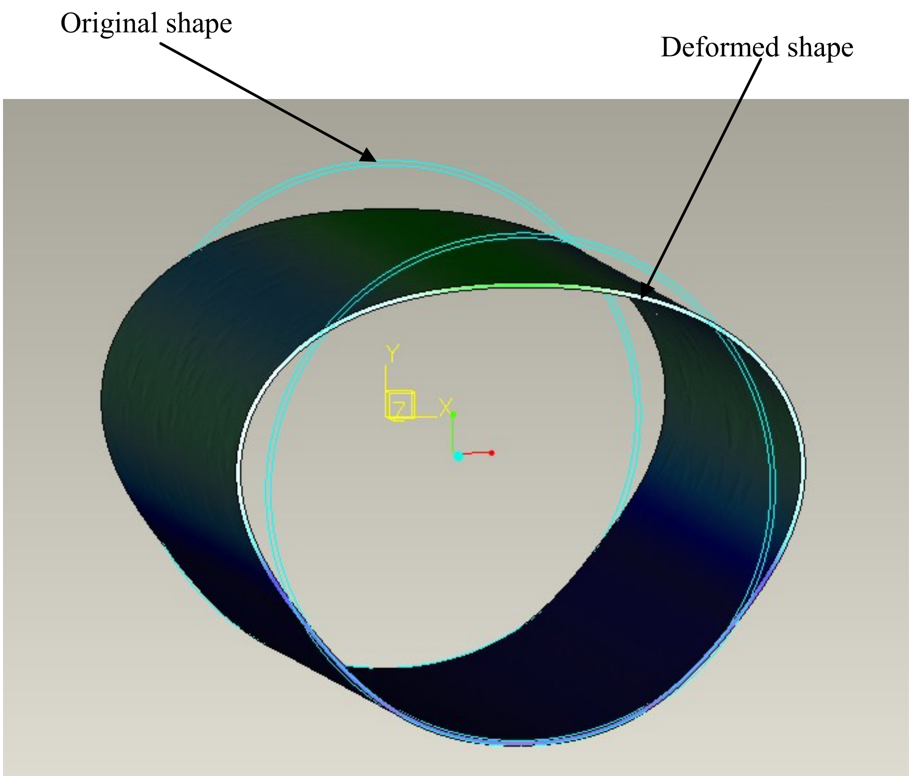


Fig 12: Kiln Shell deformation Due to Ovality (Pro-Engineer Results)

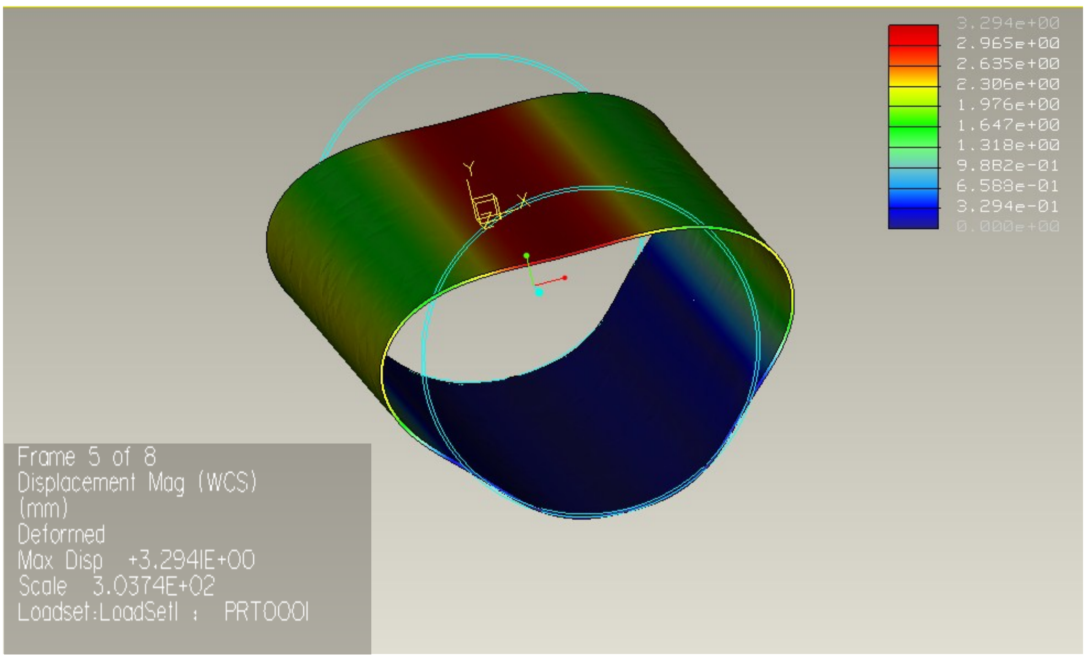


Fig 13 : Maximum clearance between tire and shell (S)=3.29 cm at temperature =200°C, tire base No.2 (90 m)

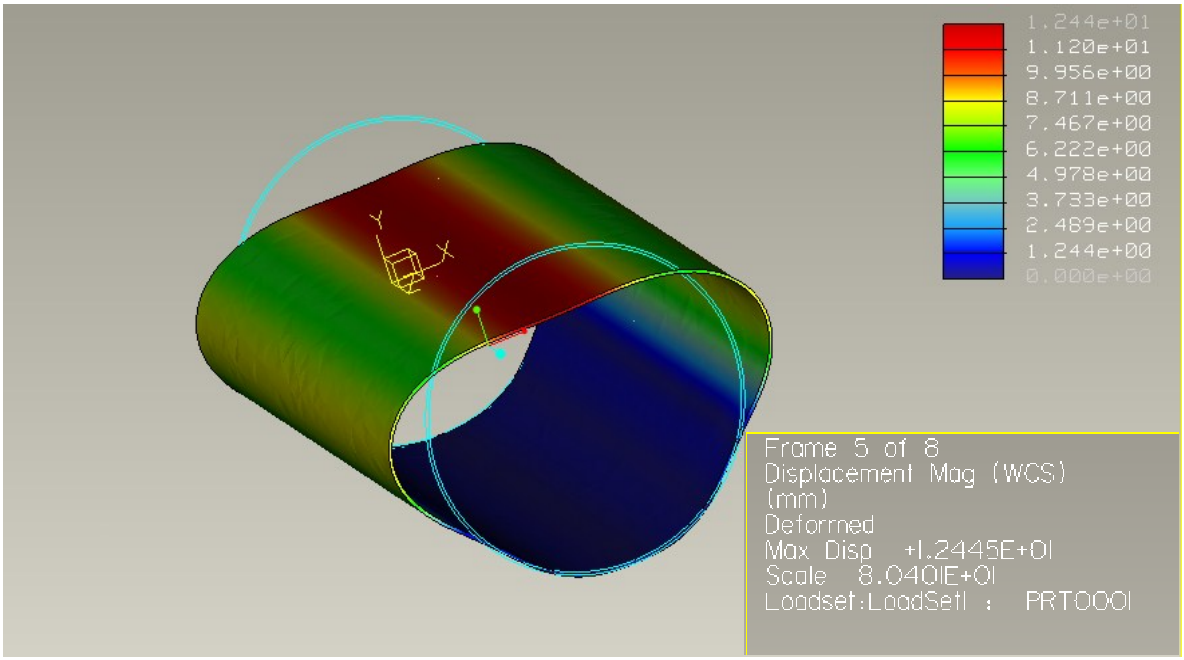


Fig 14: Maximum clearance between tire and shell (S)=12.44 cm at temperature =350^{o}C , tire base No.1 (45 m)

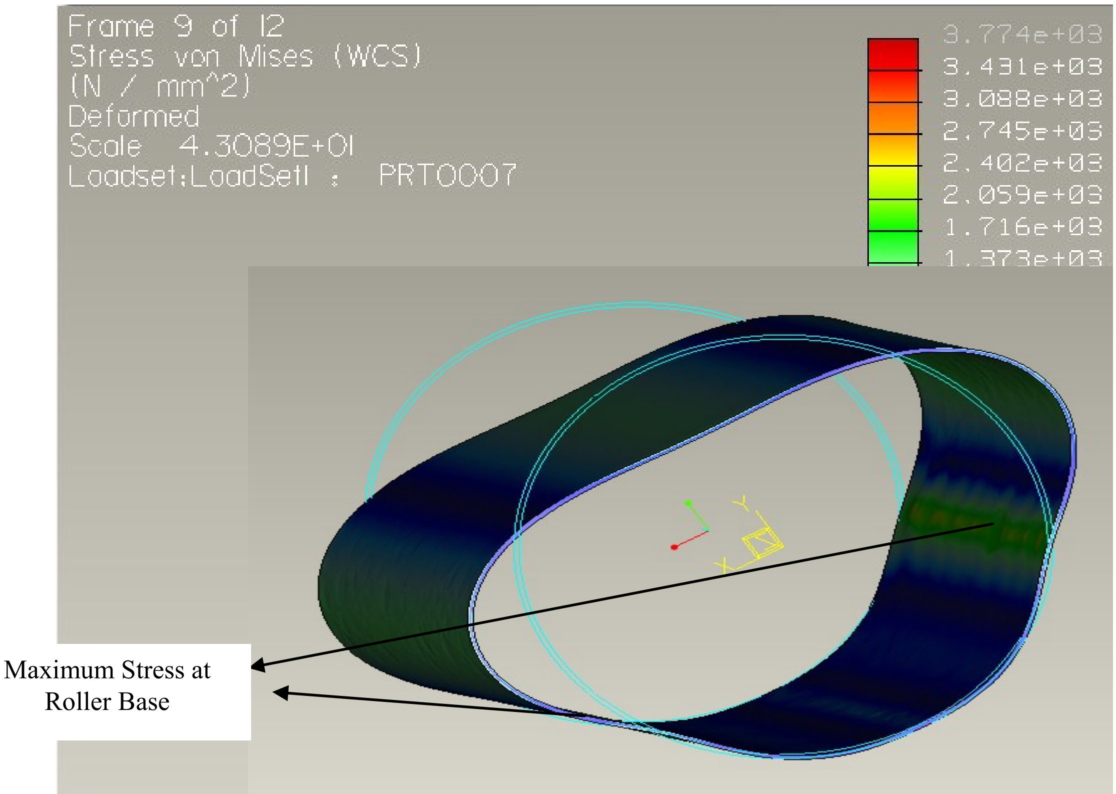


Fig 15: Stresses due to Ovality at temperature =400^{o}C

The stresses in lining brick due to Ovality are shown in Fig 16.

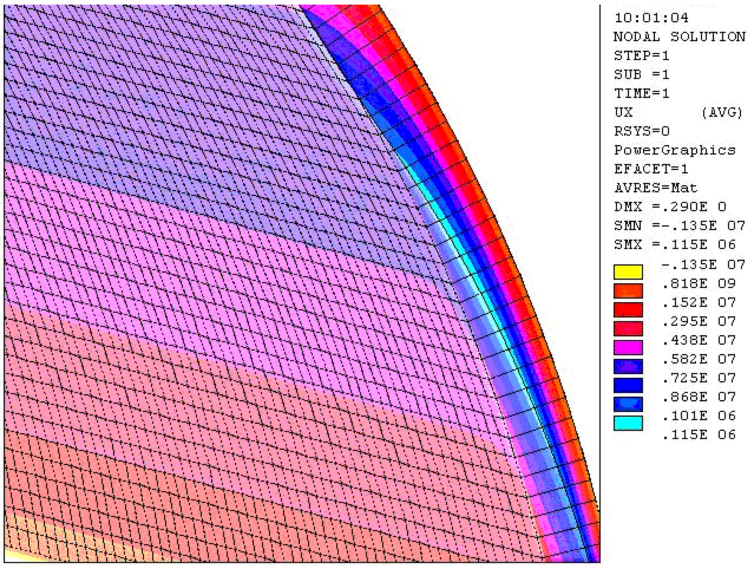
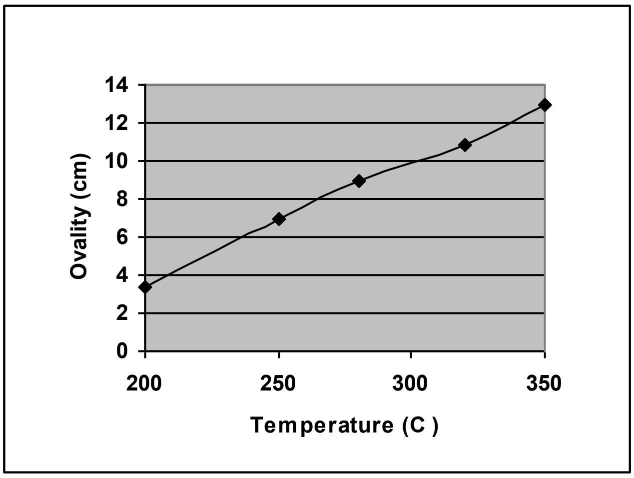


Fig 16: Stresses (N/cm^2) due to Ovality on a quarter kiln lining brick (at kiln shell temperature=350°C and brick {Alumax 75 A} temperature=1000°C) in upper transition zone.

When maximum axial stresses exceed the strength of brick which represented by MOR(Modulus of Rupture) and hot MOR the failure will occur.

Max axial stress SMX_{brick}= 18.4 MPa

So the value of maximum stress for each Alumina (Alumax 75) brick exceed the MOR (Table 1 which equal to 12 MPa) lead surely to failure.



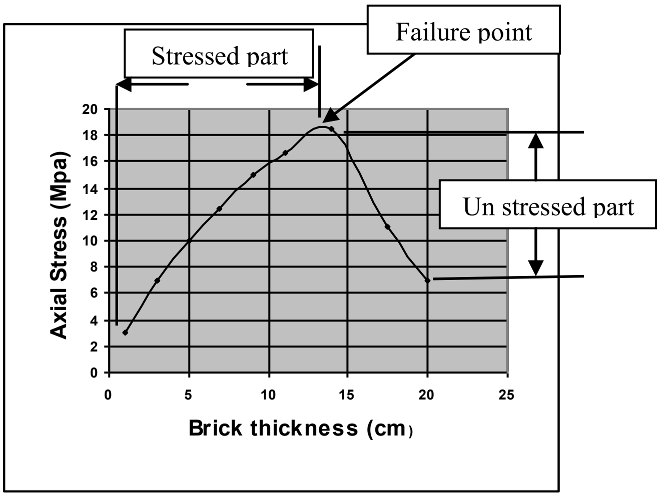


Fig 17:The Ovality Phenomena vs Temperature at tire No.1 (1st 50 m)

Fig 18:The axial stress along the brick length.

It is shown from Figure 17 that there is increasing in Ovality phenomena with increasing temperature .The stresses (as shown in Figure 18) was concentrated in the region near the last quarter (14 cm) of brick length leading to failure because of the displacement of the bottom of brick was assumed zero.

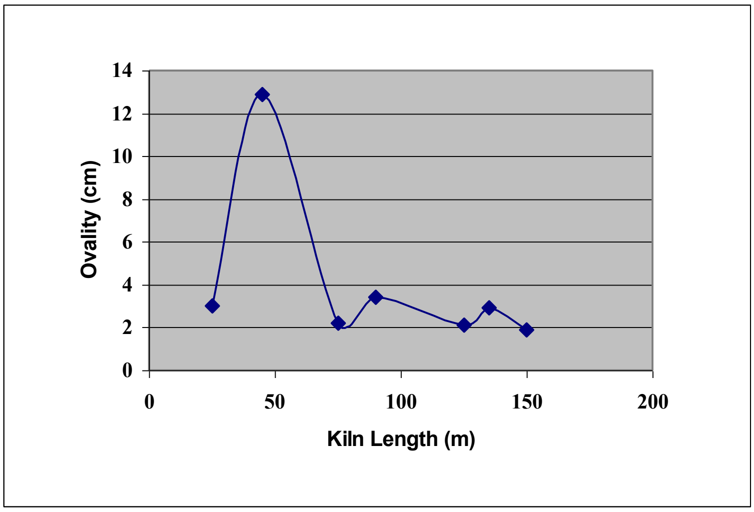


Fig 19: The Ovality Phenomena along the kiln length.

Figure 19 show the Ovality along the kiln length, it is shown that the first quarter of kiln is exposed to high deformations due to temperature increasing, as well as, it is shown that the Ovality is high on tires.

From the above results it can be concluded that the mechanism of Ovality are as following:

1. Because the tire is supported primarily at the bottom, its own weight will cause it to sit flat. This flattening of the tire makes the horizontal axis a little longer than the vertical axis.

2. Each tire has two point loads where it sits on the two support rollers. The two point loads work to straighten out the tire. As a result, the degree of curvature decreases from the nominal at each roller.

3. As the shell flexes inside the tire, a gap forms between the shell and tire .

4. The brick lining exhibit shifting, crushing lead to cracking because of compression stresses on the two sides of brick.

5- As the final results of Ovality a parts of bricks thickness will fall down as shown in Figure 20 .

Fig 20 : Ovality (about 3 months of kiln operation ,Kufa cement plant, kiln No.2,tire base No.1) about 20% of brick thickness(4 cm) is fall down.

From above results we can show what happen on lining brick during each kiln turn in Figure 21

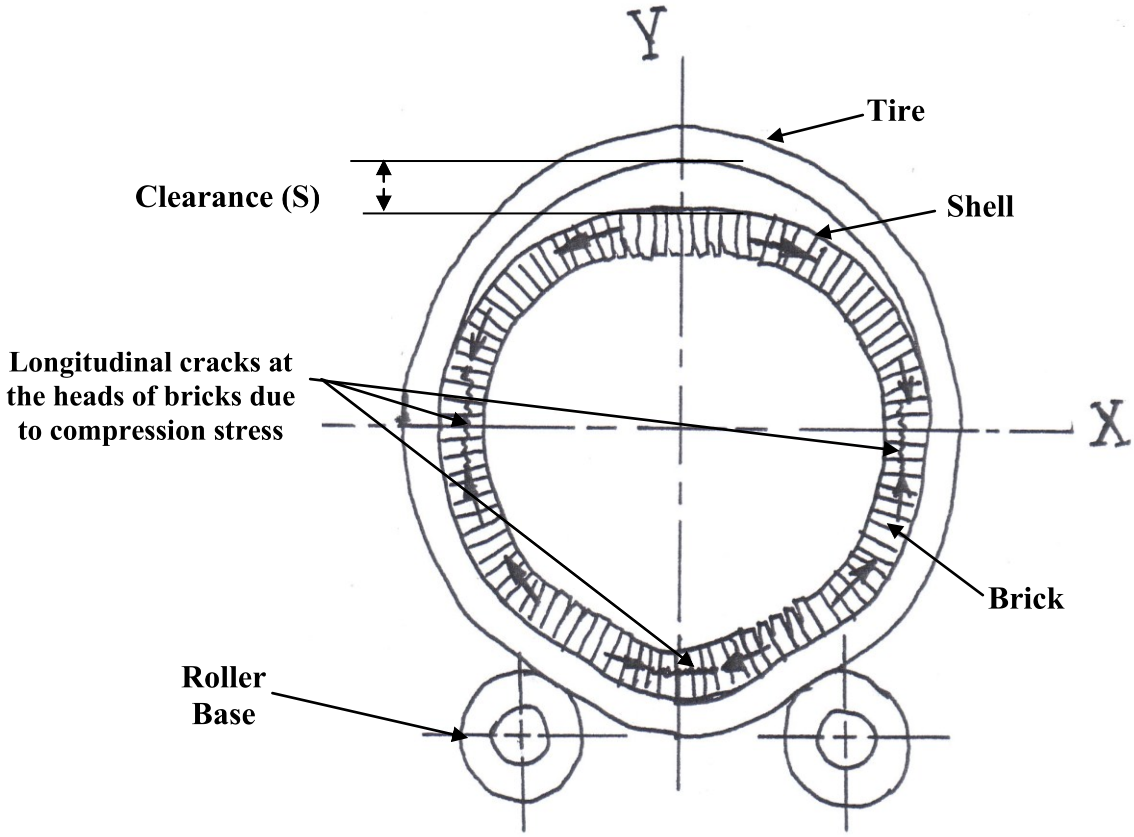


Fig 21 : Ovality condition and its effect on the brick lining (a cross section in cement kiln).

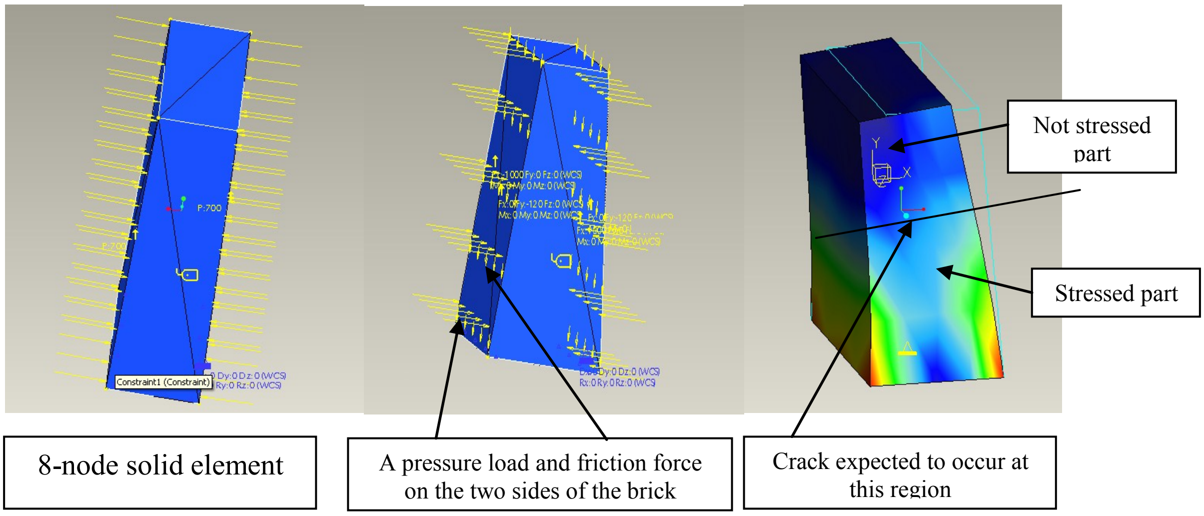


Fig 22:The type of element mesh, loads and crack expected for a brick exposed to Ovality.

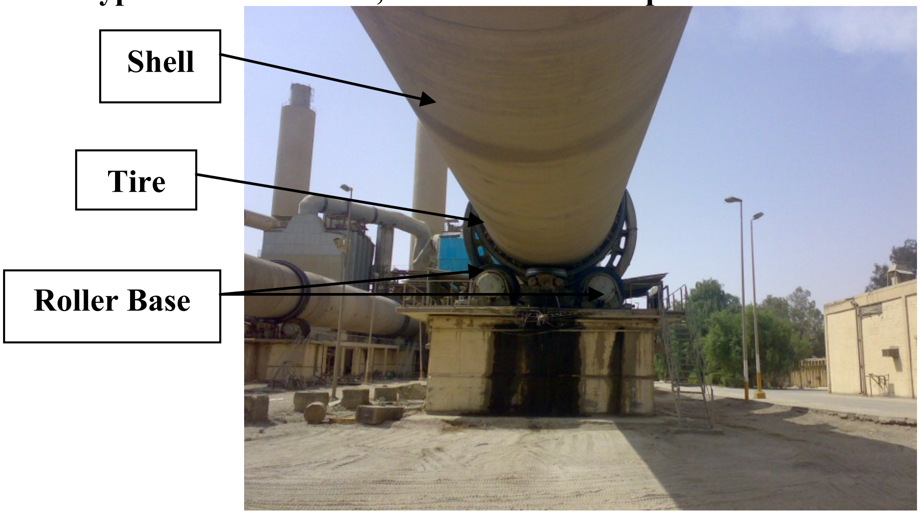


Fig 23 : Shell , Tire and Roller Base.

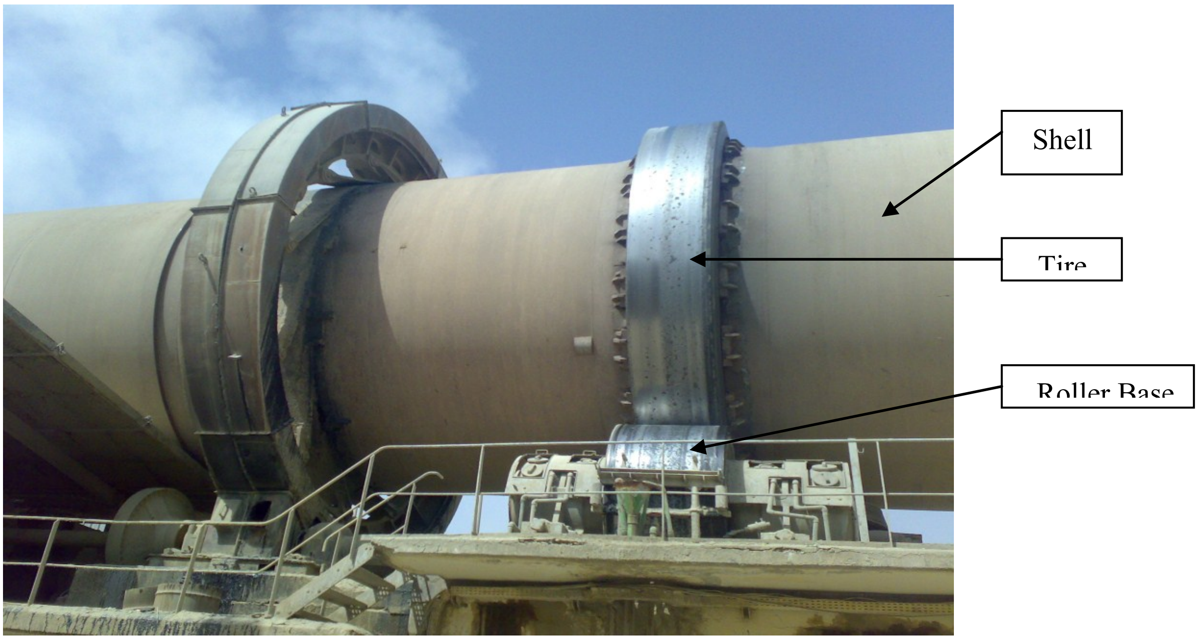


Fig 24 : Shell , Tire and Roller Base

4- CONCLUSIONS

1-Ovality occurs especially over tires or at stress points along the kiln shell.
2-The shell Ovality should be maintained between 6 cm ±1. In case the shell Ovality crosses this limit, it will have a detrimental effect on the brick lining life.

5- Recommendations :

1-Installing the brick lining at tires section by using steel plate between bricks, this plate will tight the surface of every two brick and will prevent bricks from collapse due to compression cracks.
2-Installing the brick lining at tires section must done with mortar [Resco 2001]. Mortar will absorb the vertical forces through a compressibility of the mortar bed this method was applied as shown in Figure 25.

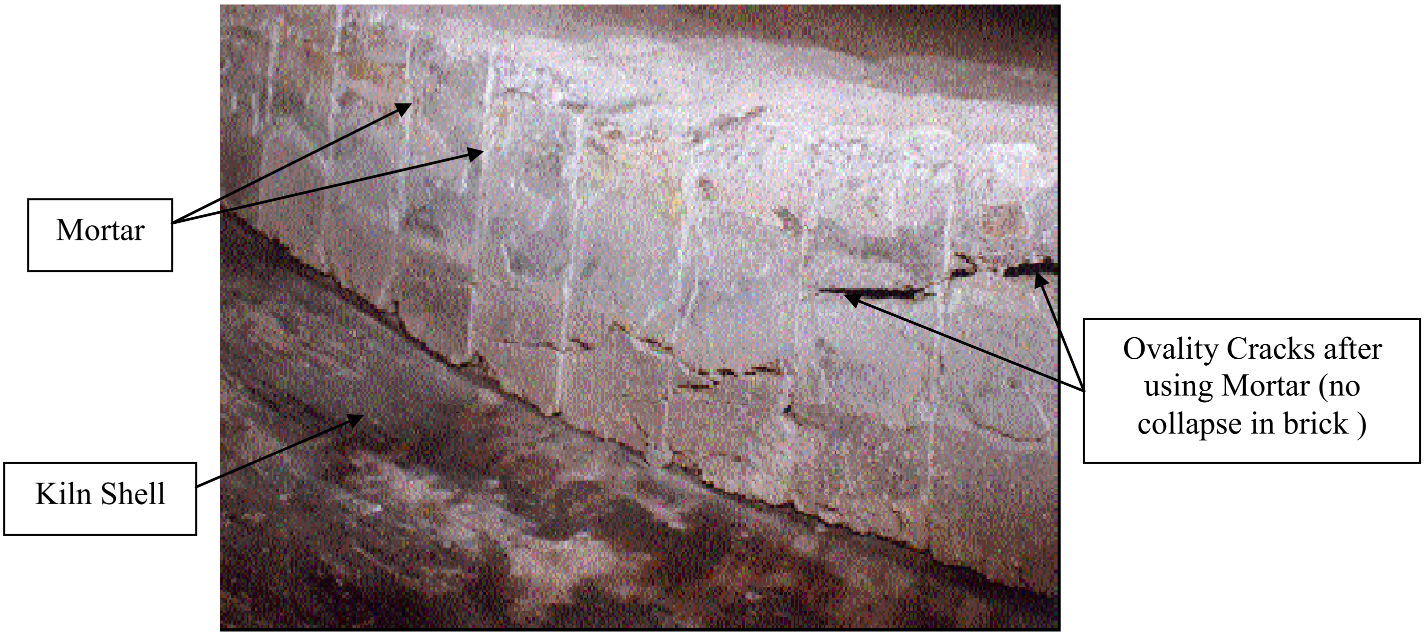


Fig 25 :Using of mortar between bricks to improve its resistance due to Ovality(Resco line Vol.2 2001).

3-A definite solution is only achieved through a close clearance for a low shell ovulation .It is strongly recommended to make a continuous checks for the tire clearance .
4-Use of external kiln shell air cooling is recommended in order to improve the development of a thicker coating, which further reduce the kiln shell temperature.
5-Continuously monitoring the tire creep, temperature of tire and shell.
6-Cooling the shell when the limits for creep and temperature are critical.
7- In the burning zones. I.e. tire 1, the brick wear rate is extremely sensitive to Ovality since large Ovality makes the coating unstable as shown in Figure 26 and subsequently the bricks are thermally stressed. Thus it is more important that the Ovality of tire 1 is especially kept within the limit for extended refractory life. So that it is recommended to study this case separately.

Fig 26: Coating falling down due to Ovality at Burning zone, Kufa cement new factory.

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Acknowledgments

We would like to thank directed to the administration of Kufa cement factory for continuous assistance and cooperation during the period of the work.

Appendix

Mechanical Solution Summary (Pro-Engineer 4 Software) tire No.1 ,T=350 ^oC

Mechanical Structure Version L-01-31:spg
Summary for Design Study "Analysis19"
Sun April 02, 2011 00:14:53

Run Settings
Memory allocation for block solver: 128.0

Parallel Processing Status
Parallel task limit for current run: 2
Parallel task limit for current platform: 64
Number of processors detected automatically: 2
Checking the model before creating elements...
These checks take into account the fact that AutoGEM will
automatically create elements in volumes with material
properties, on surfaces with shell properties, and on curves
with beam section properties.

Generate elements automatically.
Checking the model after creating elements...

Excluded elements may be required near one or more
constraints due to concentrated stresses.
No errors were found in the model.

Mechanica Structure Model Summary

Principal System of Units: millimeter Newton Second (mmNs(

Length: mm
Force: N
Time: sec
Temperature: C

Model Type: Three Dimensional

Points: 2302

```
  Edges:          11140
  Faces:          15375

  Springs:            0
  Masses:             0
  Beams:              0
  Shells:             0
  Solids:          6537

  Elements:        6537

----------------------------------------------------------

Standard Design Study

Static Analysis "Analysis19:"

Convergence Method: Single-Pass Adaptive
Plotting Grid:    4

Convergence Loop Log:                    (00:15:05(

<<  Pass  1>>
    Calculating Element Equations         (00:15:08(
      Total Number of Equations:  109573
      Maximum Edge Order:            3
    Solving Equations                     (00:15:15(
    Post-Processing Solution              (00:15:28(
    Checking Convergence                  (00:15:32(
    Resource Check                        (00:15:34(
      Elapsed Time    (sec):     41.02
      CPU Time        (sec):     40.78
      Memory Usage      (kb):    306107
      Wrk Dir Dsk Usage (kb):    370688

 <<  Pass  2>>
      Calculating Element Equations         (00:15:37(
        Total Number of Equations:  112185
        Maximum Edge Order:            7
      Solving Equations                     (00:15:43(
      Post-Processing Solution              (00:15:57(
      Checking Convergence                  (00:16:01(
      Calculating Disp and Stress Results   (00:16:03(

      RMS Stress Error Estimates:

      Load Set        Stress Error  % of Max Prin Str
----------------- ------------ ----------------
      LoadSet1        1.05e+01      0.4% of  2.51e+03
```

Resource Check (00:16:29(
Elapsed Time (sec): 95.46
CPU Time (sec): 77.17
Memory Usage (kb): 312508
Wrk Dir Dsk Usage (kb): 384000

Total Mass of Model: 2.222584e+01

Total Cost of Model: 0.000000e+00

Mass Moments of Inertia about WCS Origin:

Ixx: 2.59334e+08
Ixy: -7.88158e-04 Iyy: 2.59334e+08
Ixz: 5.26255e-05 Iyz: 1.76145e-03 Izz: 1.48238e+08

Principal MMOI and Principal Axes Relative to WCS Origin:

Max Prin	Mid Prin	Min Prin
2.59334 e+08	2.59334e+08	1.48238e+08

WCS X:	0.00000e+00	1.00000e+00	0.00000e+00
WCS Y:	1.00000e+00	0.00000e+00	0.00000e+00
WCS Z:	0.00000e+00	0.00000e+00	1.00000e+00

Center of Mass Location Relative to WCS Origin:
8.60214) e-09, -1.82606e-09, 2.50000e+03(

Mass Moments of Inertia about the Center of Mass:

Ixx: 1.20423e+08
Ixy: -7.88158e-04 Iyy: 1.20423e+08
Ixz: 5.30600e-04 Iyz: 1.65999e-03 Izz: 1.48238e+08

Principal MMOI and Principal Axes Relative to COM:

Max Prin	Mid Prin	Min Prin
1.48238 e+08	1.20423e+08	1.20423e+08

WCS X:	0.00000e+00	0.00000e+00	1.00000e+00
WCS Y:	0.00000e+00	1.00000e+00	0.00000e+00
WCS Z:	1.00000e+00	0.00000e+00	0.00000e+00

Constraint Set: ConstraintSet1: PRT0007

Load Set: LoadSet1: PRT0007

Resultant Load on Model:
in global X direction: 1.931912e-05

```
     in global Y direction: -1.666939e+06
     in global Z direction: -1.012895e-06

   Measures:

   max_beam_bending:   0.000000e+00
   max_beam_tensile:   0.000000e+00
   max_beam_torsion:   0.000000e+00
   max_beam_total:     0.000000e+00
   max_disp_mag:       1.291522e+01
   max_disp_x:        -9.094533e+00
   max_disp_y:        -1.290980e+01
   max_disp_z:         8.322410e-02
   max_prin_mag*:     -2.513795e+03
   max_rot_mag:        0.000000e+00
   max_rot_x:          0.000000e+00
   max_rot_y:          0.000000e+00
   max_rot_z:          0.000000e+00
   max_stress_prin*:   1.828063e+03
   max_stress_vm*:     3.774382e+03
   max_stress_xx*:    -4.078354e+02
   max_stress_xy*:    -1.753768e+03
   max_stress_xz*:     1.756102e+02
   max_stress_yy*:    -8.615719e+02
   max_stress_yz*:    -1.309233e+03
   max_stress_zz*:    -3.364292e+02
   min_stress_prin*:  -2.513795e+03
   strain_energy:      1.974788e+06

------------------------------------------------------------

Memory and Disk Usage:

  Machine Type: Windows NT/x86
  RAM Allocation for Solver (megabytes): 128.0

  Total Elapsed Time (seconds): 95.83
  Total CPU Time     (seconds): 77.50
  Maximum Memory Usage (kilobytes): 312508
  Working Directory Disk Usage (kilobytes): 384000

------------------------------------------------------------
Run Completed
April 02, 2011   00:16:29
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```

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