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Numerical Study of the Bonding Model Effect on Stress Distribution in Anchored Refractory

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Abstract

A refractory material is commonly used for the lining of cement rotary kilns. This is done by using cast refractory concrete reinforced with anchors which are welded to ring sector plates. While the rotary kiln is in operation these materials are subjected to significant thermal loads. This yields thermal stress which is one of the main failure causes of the concrete liner or refractory. This research proposes the development of a proper finite element model as a tool to analyse refractory strength. The analytical process is divided into two parts. In the first part, the objective is to develop an experimental setup to measure refractory-anchor stress under thermal loading. In the second part, the finite element model of a simple refractory-anchor system is used under the assumption that its mechanical behaviour is linear under varying temperatures and that the contact behaviours between the anchor and refractory material is a perfect bond and a slip bond compared to the experimental results. Under these assumptions the finite element stress results show similar results when the bond-slip model is employed. The perfect bonding model tends to over predict the stress results.

***Keywords**:* Thermal stress distribution, Anchored refractory, Bond-slip model.

1. Introduction

Refractory concretes with steel anchors are used widely in the cement industry. They are mainly applied in rotary kilns for refractory linings to maintain high temperatures and to protect the steel shells of the kilns from high temperatures and corrosive materials. It has been found that fire resistant concrete is damaged by thermal stresses resulting in cracking. Therefore, it is imperative that engineers design tools, such as computer aided design systems to create durable refractory linings.

Past research has presented models of finite element non-linear problem stress bond looking into the interaction between concrete and steel reinforcements. Alaka [1] and Lamya used a finite element nonlinear model software (ABAQUS) to determine the value of both the radial and circumferential stresses created by an increase in the volume of steel reinforced concrete, which is a cause of cracking in concrete. The model takes into account pressure loss and a decrease in the coefficient of friction interface surface. The researchers conducted pull-out tests to compare the results with the model, confirming the results. Research by Wygant and Crowley [2] has proposed a relationship between stress and strain resulting in linear elasticity, linear shrinkage, uniform thermal conductivity and modulus of elasticity for the calculation of the maximum stress lining requiring a steady-state temperature of the system lining Fluid-Bed Catalytic Unit (FCU).

The purpose of this research is to propose a method to study the interaction between refractory concrete and reinforcement by using a finite elements method.

The proposed method is composed of

1. The FEM model in which the bonding between refractory concrete and steel anchor is based on the fixed (perfect) bond.

2. The FEM model in which the bonding between refractory concrete and steel slip (bond-slip model) by the appropriate model is used to analyse the stresses in the lining of kilns in the future.

2. The FEM Model in which the interaction between refractory concrete and steel anchor is bond-slip model.

Refractory concrete consists of chemical substances which are Alumina, Silicon Carbide (SiC), Oxide iron and Calcium Oxide in the ratio of 48%, 30%, 0.6% and 1.3% in sequence. The quantity of Calcium Oxide determines the classification of refractory material (1.0-2.5% is classified as a low cement refractory concrete, 0.2 - 1.0% as ultra-low, and up to 0.2% as no cement concrete). Refractory materials can tolerate temperatures up to 1,500 °C. Their density after a drying process at 110 °C is 2,730 kg/m^3. Young's modulus of bending after heating at 100 and 1,000 °C are 130-140 kg/m^3 respectively.

2.1 Appearance and structural components of the cement kiln

In this paper, a cylindrical shaped test cement kiln with 5 meters diameter, placed at a 1-4 degree angle out of the horizontal position is consider. It rotates around its centre at 30 – 250 rounds/hour. The shell of the kiln is fabricated from 0.05 meter thick carbon steel and lined with refractory material and steel anchors. The method of operation is to firstly feed raw cement material through the "feed-in channel" at one side of the kiln as shown in Figure 1: Appearance of cement kiln. When the kiln is rotating, cement material falls into the downside end. Hot air is moved along the cement kiln in counter-rotation direction creating very high temperature or possibly flames inside the cement kiln through the burner. Afterwards, the cement material is processed under highest temperatures and passed through the "Nose ring" as shown in Figure 1 before falling into a cooler.

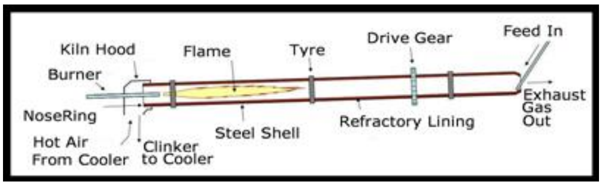

Figure 1: Appearance of cement kiln

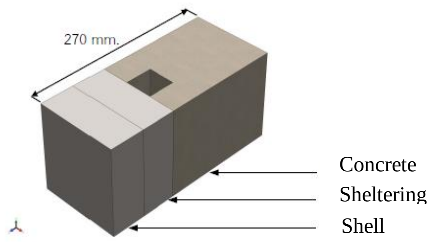

Figure 2: Cross-section of cement kiln component

a. Thermo-mechanical properties of refractory material

The kiln is composed of refractory material (And-LCC) with stainless steel (310S) anchors, steel sheets. The kiln shell is carbon steel. The thermo-mechanical properties are shown in Tables 1 and 2.

Table 1: Thermo-mechanical properties of refractory material, stainless steel and carbon steel [3-6]

Material	T (°C)	E (GPa)	T (°C)	α ($\times10^{-6}\cdot°C^{-1}$)	T (°C)	ν
Refractory	110	68	450	7.6	110	0.15
	250	50	900	7.6	1100	0.23
	500	44				
	700	39				
	900	21				
	1100	13				
Stainless Steel	100	200	100	15.9	20	0.30
	200	185	500	17.1		
	400	170	1000	18.9		
	800	135				
Carbon Steel	100	200.6	100	11.70	25	0.29
	200	197.2	200	12.06		
	300	193.7	300	12.42		
	400	191.0	400	12.78		
	500	186.8	500	13.14		
	600	182.0	600	13.32		
	700	174.4	700	13.68		

* Symbol T, E, α and ν represent temperature, the Modulus of Elasticity, the Coefficient of Thermal Expansion and the Poisson Ratio in sequence

The coefficient of thermal expansion, modulus of elasticity and Poisson's Ratio are varying with temperature changes as shown in Tables 1 and 2.

Table 2: Thermal conductivity of refractory material and carbon steel [3-6]

Material	T (°C)	Thermal Conductivity ($W\cdot m^{-1}\cdot°C^{-1}$)
Refractory	100	1.30
	600	1.33
	1400	1.65
Stainless Steel	100	13.80
	200	13.95
	400	16.28
	500	18.70
	600	19.77
Carbon Steel	100	47.77
	200	48.11
	300	47.25
	400	45.86
	500	44.48
	600	43.10
	700	41.71

b. Properties of flexible refractory material

The properties of a flexible refractory material compression stress and modulus of elasticity from compression test are shown in

Table 3: Properties of refractory material

Temp (∘C)	Max.Stress (MPa)	Modulus of Elasticity (MPa)
27	60.2	2912
200	33.4	1385
400	77.4	3040
600	104.1	3438
800	85.6	2190

c. Properties of plastic refractory material

The compressive stress f_c of concrete is calculated by using the formula in (2.4.1). The results of the calculation shown in Figure 3 are the relation between compressive stress and strain for temperature range 30, 200, 400, 600 and 800 degree Celsius.

$$\varepsilon_c^{'} = \frac{f_c^{'}}{E_c}\left(\frac{n}{n-1}\right) \qquad \textbf{(2.4.1)}$$

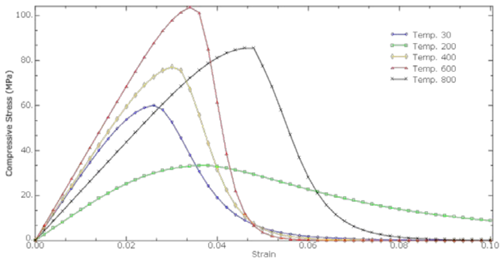

Figure 3: Relationship between compressive stress and strain of refractory material at 30, 200, 400, 600 and 800 degree Celsius

The plastic material strain is calculated by using **Error! Reference source not found.**.4.2) and **Error! Reference source not found.**) in order. The graph is plotted between compressive stress and plastic strain of concrete as shown in Figure 4

$$\varepsilon_{pl} = \varepsilon_t - \varepsilon_{el} \qquad \textbf{(2.4.2)}$$

$$\varepsilon_{el} = \frac{f_c}{E_c} \qquad \textbf{(2.4.3)}$$

When;

ε_t : Total strain

ε_{el} : Flexible strain

ε_{pl} : Plastic strain

f_c : Compressive stress at ε_t

E_c : Modulus of elasticity

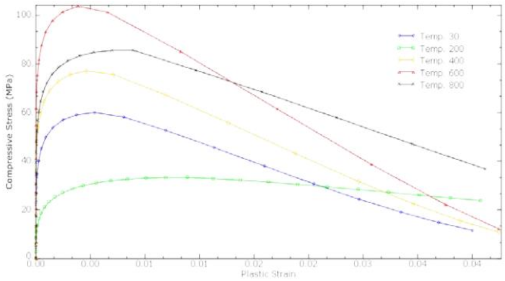

Figure 4: Relationship between compressive stress and plastic strain of refractory material at 30, 200, 400, 600 and 800 degree Celsius

3. Finite Element Modelling

Chemical bond is calculated by modelling contact pressure and friction force between refractory anchor and concrete. Both, flexible and plastic properties are defined in non-linear characteristics. The following analysis method was used:

1. Specify the model
2. Determine the property of refractory anchor and concrete
3. Determine the contact surface and attributes of refractory anchor and concrete connection
4. Define constraint and load
5. Create mesh

3.1 Simulation of refractory properties

The non-linear behaviour of refractory concrete is represented by two properties which are elastic properties and plastic properties

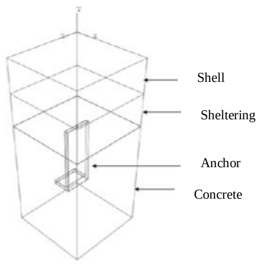

Figure 5: Components of the model

3.2 Contact surface modelling between refractory anchor and concrete

Normally, in an engineering problem that has contact surfaces between two elements or more, a friction force occurs on the object and creates resistance of motion (slip motion).

The method of defining contact modelling contains three steps:

1. Determine object's surface which has potential in contacting
2. Determine surface properties that effect to other surface
3. Determine thermo-mechanical reaction of model under contacting behaviour

3.2.1 Modelling contact pressure and friction condition

As method of determining the mechanical reaction on the surface model we follow the ABAQUS Analysis User Manual [7]

1. Friction force (reaction force between contacting surface)
2. Surface relative velocity
3. Softened contacting (reaction in perpendicular between surfaces)

3.2.2 **Modelling the contact pressure**

The contact pressure for concrete and steel bonding at p^0 is inversely proportional to the concrete cover thickness. The difference of p^0 is determined by using a regression equation analysis. The equation represents the relation between the contact pressures at zero gap and the concrete cover thickness. These can be used for calculating contact pressure for the concrete. Equation 3.3.1 determines the relationship between contact pressure and the concrete cover thickness with the results shown in Figure 6.

$$p^0 = 0.128C + 1.5 \qquad 3.3.1$$

When

p^0 = contact pressure

C = concrete cover thickness

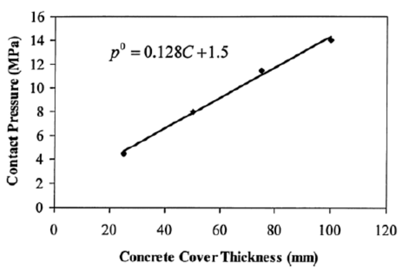

Figure 6: Differentiation of contact pressure and concrete cover thickness

3.2.3 Modelling friction on steel and concrete bond

Lundgren and Gylltoft (2000) developed the relationship between friction coefficient and slip coefficient using the test of Tepfers and Olsson (1992). Lundgren and Gylltoft found that the value of the static friction coefficient μ_s =1 and the kinetic friction coefficient μ_k = 0.4 with both values varying exponentially from the static to the kinetic condition. Later, Alaka adjusted the value of that friction coefficient to be more suitable. The different values of the decaying function should be less than 1, as shown in. With a variation of friction coefficient and slip coefficient for different values of d_c it is clear that the curve of matches well with the Lundgren and Gylltoft curve. Therefore, the model in this section is using Alaka's data for the inputs in the ABAQUS software. With a Static Friction Coefficient of μ_s =1, for example, the Kinetic Friction Coefficient is μ_k =0.4, and the Decay Coefficient is d_c = 0.45.These results are used in equation 2.4.1 to calculate the slip with varying Friction Coefficient. Figure 8 shows the correlation of Friction Coefficient and slip between anchor steel and refractory interface.

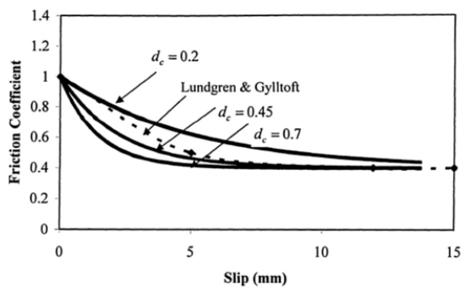

Figure 7: Friction model for different decay coefficients [1]

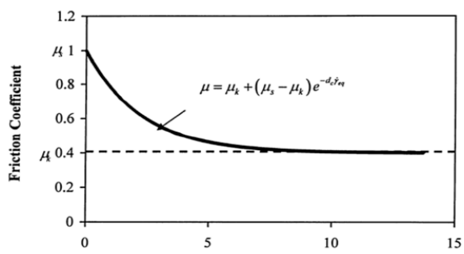

Figure 8: Exponential decay friction model used at the anchor steel and concrete interface [1]

3.3 Boundary condition of the model

Normally the stress from expansion due to heating is greater than the stress of gravity force. Thus, the stress from heating is of higher concern [9]. The model shows that under a heating condition at 700°C, the refractory weight is neglect able. The boundary condition of displacement and temperature at this point equals zero and the heat transfer to the surrounding environment is at 35°C by convection with a Convection Coefficient of 190 W/m2·°C-1 [8] as shown in Figure 10

3.4 Creating a mesh

The elements of the model are determined by a hexahedral shape (8 nodes) for both anchor steel model and refractory model as shown in figure 9.

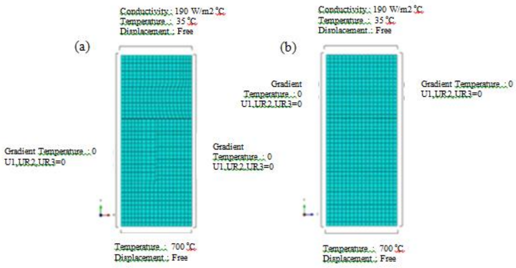

Figure 9: Boundary condition of temperature and displacement a) X-Y plane b) Y-Z plane

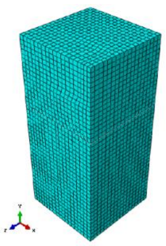

Figure 10: Assigning the element in Finite Element Model Perfect bond model

The perfect bond model is created similar to the bond-slip model but the mechanical behaviours of all refractories are linear varying by temperature. The bonding between anchor steel and refractory interface are permanently no-slip bonds. Figure 10 shows the model after applying the mesh.

4. Validation of the Finite Element Model

Validation of the stress from the Finite Element Model method and comparing it with the average results from the two experiments were in under heating conditions. The kiln was creating heat source for heating the sample in the area which have thermocouple and strain gauge installed at the sample for measuring actual temperature and stress as shown in Figure 11 and12

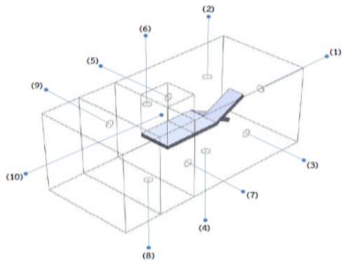

Figure 11: A testing sample connected with thermocouple at points 1 to 10

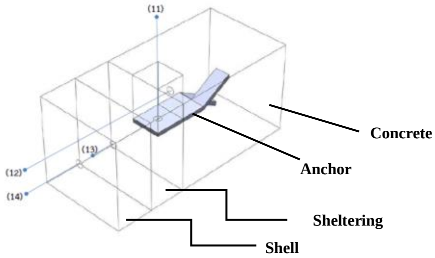

Figure 12: A testing sample connected with thermocouple at points 11 to 14

The testing started with heating the sample under controlled heating conditions by using a voltage regulator. The heating rate is at 2.5 °C/min until reaching 100°C and maintaining the temperature for 30 minutes, after which the heating is increased at previous rate until reaching 200 °C and maintain stable for another 30 minutes. These temperature increases are resumed until reaching 700°C at which point the temperature is maintained until the end of the experiment. The total time of the experiment was 17.5 hours.

The heating plan of the sample is shown in Figure13.

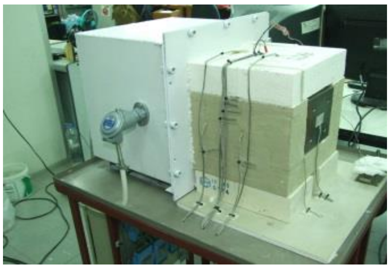

Figure 13: The experimental setup of simple anchored refractory system

5. Simulation of Bond Model Effect

The experiment was repeated two times. The experimental results were recorded by computer, comprising of temperature data at refractory surface (point 1) shown in Figure 14 after heating and maintaining the sample under a stable temperature of 700 °C. At the same time environmental temperatures (point 2 – 10) were taken as shown in Figure 15 and also the temperatures of the refractory steel anchor and shell of cement kiln (point 11 – 14) as shown in Figure 16 of the results of the anchors' strain will be compared between the model and experimental results.

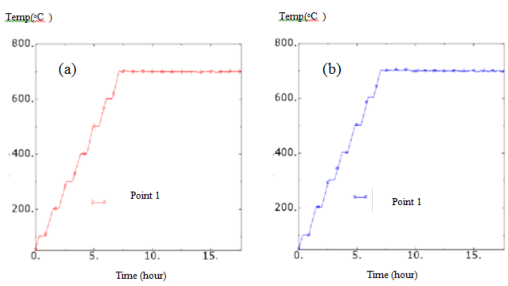

Figure 14: Temperatures refractory surface At point 1 a)1st experiment b)2nd experiment

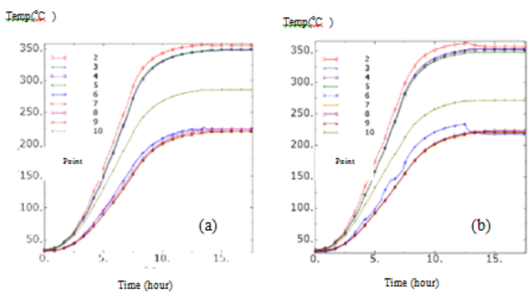

Figure 15: Temperatures in surrounding environment at point 2 – 10 a) 1st experiment b) 2nd experiment

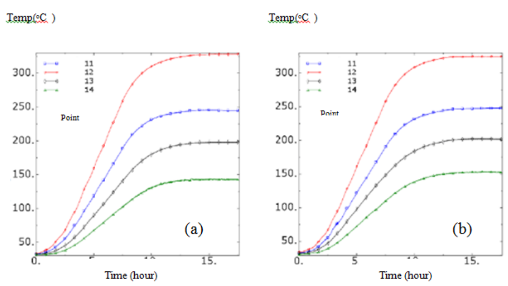

Figure 16: Temperature at refractory surface anchor and shell surface at points 11 - 14 a) 1st experiment b) 2nd experiment

5.1 Comparison of the study and experimental results

The results are presented in the form of temperature distribution, strain and steel anchor according to the Y axis is

a) the distribution of temperature and

b) strain on the steel anchor

c) Von Mises Stress consistent as well.

The different values are a) 1.85% and b) 2.5%. This demonstrates that the model can be used to analyse the stress distribution as actually occurred, as shown in Figure 17.

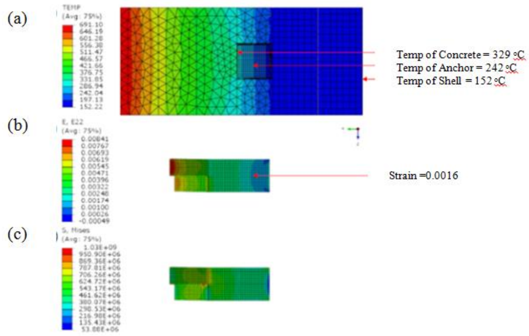

Figure 17: The result of model (a) distribution temperature (b) Anchor strain according to Y axis(c) Von Mises Stress

5.2 Comparison of the model analysis and experimental results

The experiment provided both data on the temperature and the strain on the steel anchor as a function of time until those parameters reached a steady state in accordance with the model which is also set in steady state. Therefore, the comparison of the results under steady state of steel anchor temperature, kiln shell temperature and steel anchor strain are selected from the average of two experiments.

The differences between simulation results and experimental results are displayed in Figure . They show that the temperature and the strain from both results are acceptable and consistency

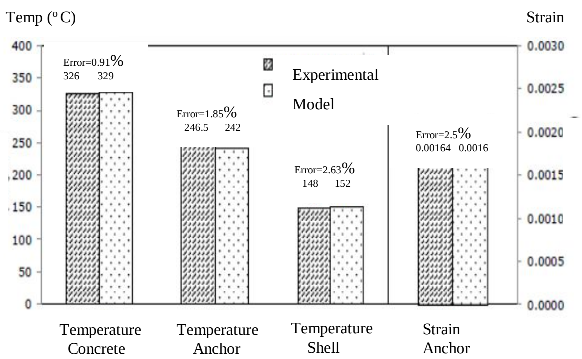

Figure18. Comparison of the simulation results with the experimental results at steady state.

5.3 Comparison of "Bond-slip" and "Perfect Bond" under heating condition

The mechanical behaviour of refractory is defined in the model in two characteristics, which are firstly the linear mechanical behaviour varying according to temperature and perfect bond between refractory and anchor, and secondly the non-linear mechanical behaviour varying according to temperature and bond-slip between refractory and anchor. The analysis of the model has shown that the first characteristic has a five times greater maximum principal stress in refractory than the second characteristic.

The stress distribution in the steel anchors are in difference forms [Figure 19]. The Von Mises Stress at the base of the anchors are similar between both models, unlike the adjacent area the stress distributed differently throughout the whole piece as shown in Figure 20.

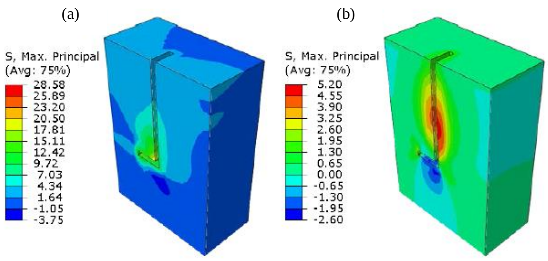

Figure 19: Comparison of the result of maximum principal stress of refractory a) linear mechanical for perfect bond and b) non-linear mechanical behaviour for bond-slip.

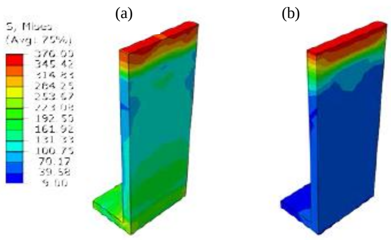

Figure 20: Comparison of Von Mises Stress result of ductile iron a) Linear mechanical behaviour perfect bond b) Non-Linear mechanical behaviour; bond-slip

6. Conclusion.

Stress distribution of refractory concrete value should be below tension stress at anchor position and faded at the further point because as a result of thermal influence steel can expand more than a refractory concrete. Regarding to this, a refractory concrete will expand under compression stress. In conclusion non-linear mechanical behaviour and slip bond model is more precise and realistic than the perfect bond model.

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