

# FEA and FMA reveal weak spots in rotary kiln designs

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## Introduction

Historically the design of the rotary cement kiln has been less than an exact science. The 'classic design theory' is the mechanism that has driven, and in many cases is still driving, kiln configurations. While it is beyond the scope of this article to discuss the particular variables that influence the kiln design, it is important to understand that some factors are process dependant and some are not.

Kiln slope, diameter, and length coupled with rotational speed are the main process dependant variables. One can not make a change to any of these components without having a dramatic effect on the kiln's production capacity. Other design components such as pier spacing and kiln inlet and outlet overhangs can be dramatically manipulated without having any effect on the kilns production rate. Experience in design evaluation of rotary kilns using finite element analysis (FEA) and fracture mechanics has shown that the classic design approach, as it applies to pier spacing and kiln overhangs, is inappropriate in many cases.

The classically designed kiln will have an overhang at the discharge end approximately 1.3 times the kiln diameter in length. Similarly, the kiln overhang at the feed end should be approximately 3 times the kiln diameter. The quantity and location of additional roller support stations are traditionally

determined by making use of beam formulas. It is common practice to force approximately equal reactions, thus standardizing as many components as possible. The utilization of beam formulas requires the design to be simplified so that the kiln structure can be treated as an elastic beam. In this process, section properties are calculated, support locations are estimated, and the reactions are determined using various concentrated and distributed loads to simulate the anticipated kiln loading. Great consistency in this approach has been observed throughout the industry. This design theory has crossed the boundary lines established by various manufacturers, as well as the boundaries of time. Much of the theory's longevity is due to a much older design principle, that states, "If it works - don't fix it!"

## FEA and Fracture Mechanics

In the last decade FEA has become the most popular tool for evaluating engineering design variables. Theories are available to evaluate stress, heat transfer, fluid flow, dynamic response, plasticity, creep and other critical phenomena. Results, rich with decision making information, offer engineers new ways of achieving performance improvements, cost reduction, increased quality, and new levels of reliability.



Figure 1. Catastrophic kiln failure.



**Figure 2. The finite element model for a rotary kiln includes the shell, the riding rings and the ring gear.**

Another state of the art technology which has been employed in modern design evaluations is Fracture Mechanics Analysis (FMA). This technology translates the magnitude of stresses into a more understandable term, namely life expectancy. The combined power of these two tools demands that engineers rethink traditional logic.

The traditional beam analysis is lacking because it treats the rotary kiln as an elastic beam rather than a thin shell structure. The resulting shell stress magnitudes, as determined by beam analysis, will be underestimated, especially at the roller support locations. This approach may be acceptable in the preliminary design stage where approximate reactions are required to determine tyre, roller, and bearing sizes. But to truly evaluate the design of a rotary kiln, an accurate calculation of the stress magnitude in the shell, especially in the vicinity of the welds, should be performed. This stress analysis should be done as a thin shell structure interfaced with solid bodies. It should come as no surprise that most of the failures associated with rotary kilns occur in the vicinity of welds. The fatigue life of the welds is very sensitive to the alternating stresses produced as the kiln rotates. This is especially true of the higher speeds, and load cycles, that are normal in the cement industry.

The alternating stresses are critical to understanding the magnitude of the stress field that is encountered at each point of the kiln shell, along an axis, as the kiln rotates. The circumferential fatigue stresses are the result of the applied

load that is working to force the kiln shell out of round. The axial fatigue stresses are the result of the applied load that is bending the structure along its axis. In keeping with the fact that the structure is rotating, it is important to keep in mind that these maximum and minimum stresses are encountered by each point along the kiln two times per revolution. In the sign convention the negative numbers show a compressive force is acting on the structure. Positive numbers show that a tensile force is present. Of primary concern are the extremes that are encountered as the kiln rotates. It is important to investigate both the inside and outside surfaces of the shell, rather than selecting an average, or mid-section locations, in order to determine the stress range present in the structure.

## Capabilities

In 1991 A-C Equipment Services embarked on a programme to develop a computer program to predict the behaviour of a rotary kiln under various loading conditions. Working together with engineers from the company's Engineering Analysis Group, a parametric model was developed that allows an accurate simulation of the effects of chain, refractory, coating thickness, load density, and the angle of repose of the load on the structure. In the design optimization process the model is subjected to various loading conditions, using various pier spacings, and then the effect on the support reactions, shell stresses, deflection, and deformation is assessed.

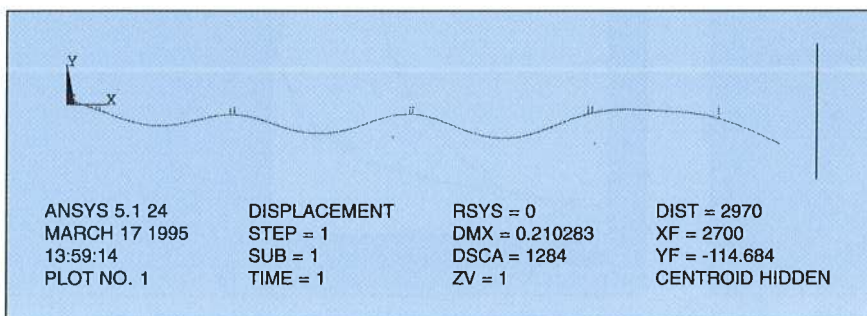
The parametric nature of the design inputs greatly simplifies the change process. This approach makes the design review portion of the design procedure much more open. Making the "What if ...," scenario an integral part of the procedure, invites input from participants who might otherwise be out of the loop.

As word of this new capability reached the market, customers with recurring shell cracking problems, unacceptable refractory life, and bearing failures turned to A-C Equipment Services to use the power of this tool to determine a cause for these failures. The primary objective in these investigations is to suggest a repair that truly addresses the root cause. Over the past three years the company have modelled over a dozen kilns, the majority being cement kilns. The correlation between the predicted result of the loading which the model was subjected to and the actual maintenance history of the kilns in question has been excellent.

Each of the analyses have been unique in some way. An analysis of a lime kiln showed the effect of large process rings that develop upon the introduction of non-condensable gases into the kiln. An analysis of a proposed cement kiln modernization demonstrated the effect of pier spacing on the fatigue life of shell welds and on riding ring thrust. Another analysis showed the dramatic effect of a 1/2 in. vertical misalignment on the fatigue life of the kiln shell. At another cement plant the effect of a planned increase in production rate coupled with an increased chain load on kiln shell and refractory lives was investigated.

## Procedure

The finite element model for the kiln assembly shown in Figure 2 includes the shell, the riding rings, and the ring gear. Non-linear gap elements were used at the interfaces to automatically evaluate the reaction between the shell and the riding rings. A computer code was developed to calculate the alternating fatigue stress along the shell per ASME codes for the non-welded shell and per Section BVS5400 of the British Welding Society or



**Figure 3. The traditional beam analysis treats the rotary kiln as an elastic beam.**

AWS Structural Welding Code for the welds. Design modifications are made utilizing this program to achieve the required operating life of the rotary kilns.

The report format can be somewhat varied, depending upon the nature of the problem being investigated. Tables are provided to show the basic results. Comparisons are usually made between a normal operating condition and various worst case conditions. The variations in the alternating stresses, circumferential fatigue stresses, and axial fatigue stresses that are present at both the outside and inside surface of the kiln shell at all points along the kiln axis are compared. Stress levels in excess of preset limits are flagged, or reported in an individual summary table.

The postprocessing capability of most FEA software make it possible to graphically represent the stress fields. Plots showing the circumferential and axial fatigue stresses that are present at the outside and inside surface of the kiln

shell are provided. These plots are colour coded showing the various stress fields that the shell passes through as it rotates. Many plotting formats are available. Each will require some imagination and visualization skill on the part of the analyst.

The usual presentation will show the kiln shell as a flat development. The picture is in essence a snapshot of the stresses present at the surface of the kiln shell. The surface being represented may be either the inside or the outside of the kiln shell. A vertical line drawn across the plot is representative of the stress levels encountered by every point of the shell circumference at that particular axial location on the reference surface, as the kiln rotates. This capability makes it much easier to visualize what is happening, but this is still a far cry from understanding it.

To assist understanding the FEA results the use of fracture mechanics is employed. Here the coded programs

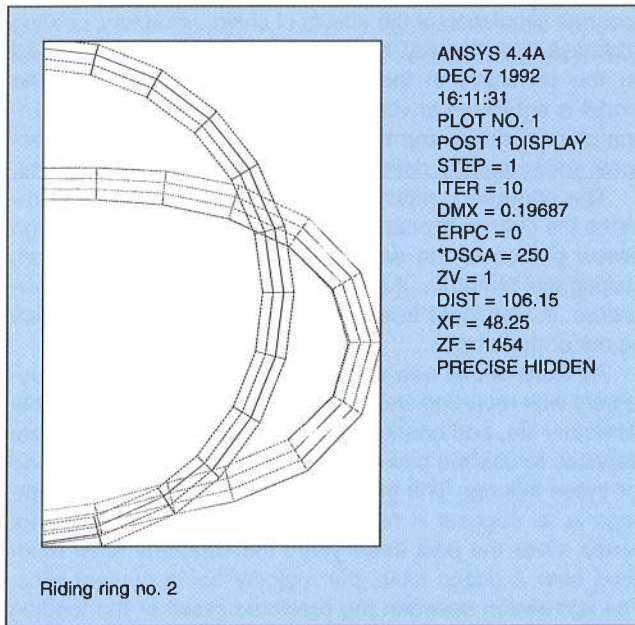


Figure 4. Riding ring no. 2 deformation under worst case condition.

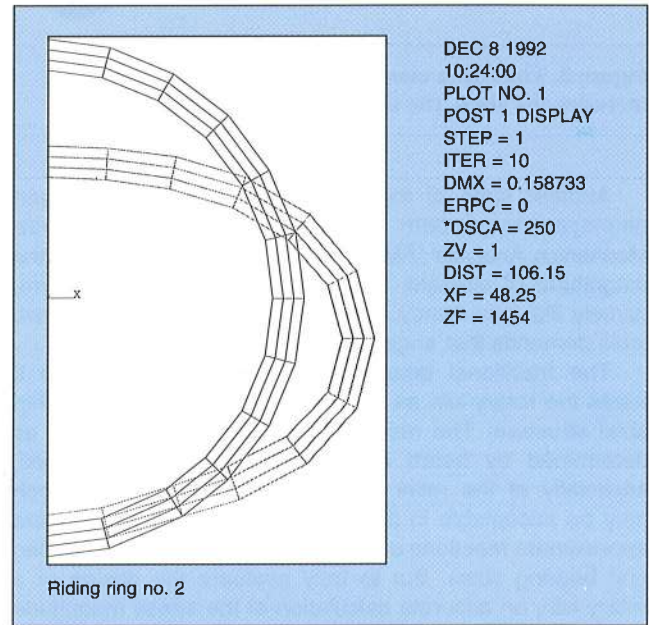


Figure 5. Riding ring no. 2 deformation under normal operating condition.

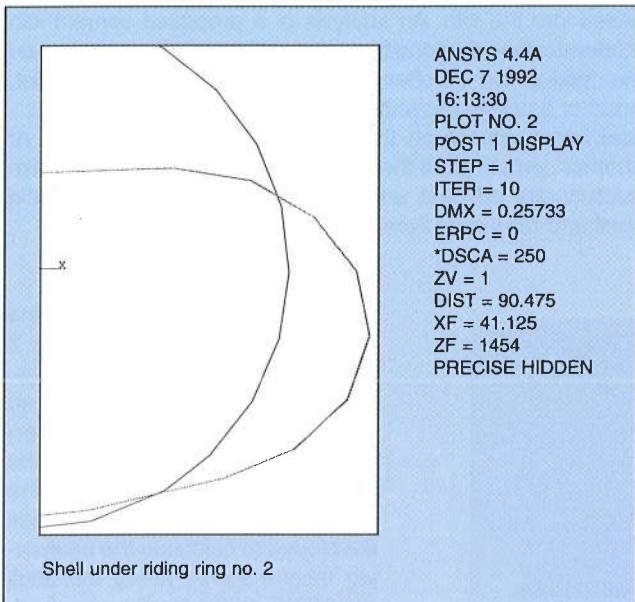


Figure 6. Shell deformation at no. 2 riding ring location, worst case condition.

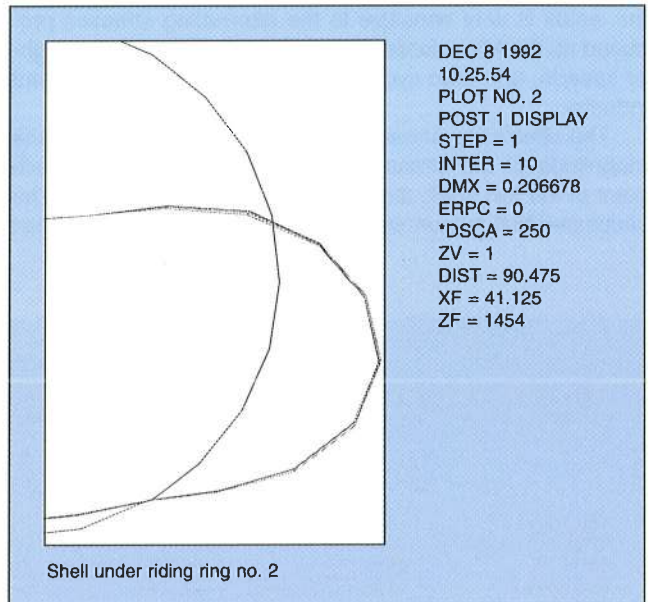


Figure 7. Shell deformation at no. 2 riding ring location, normal operation condition.

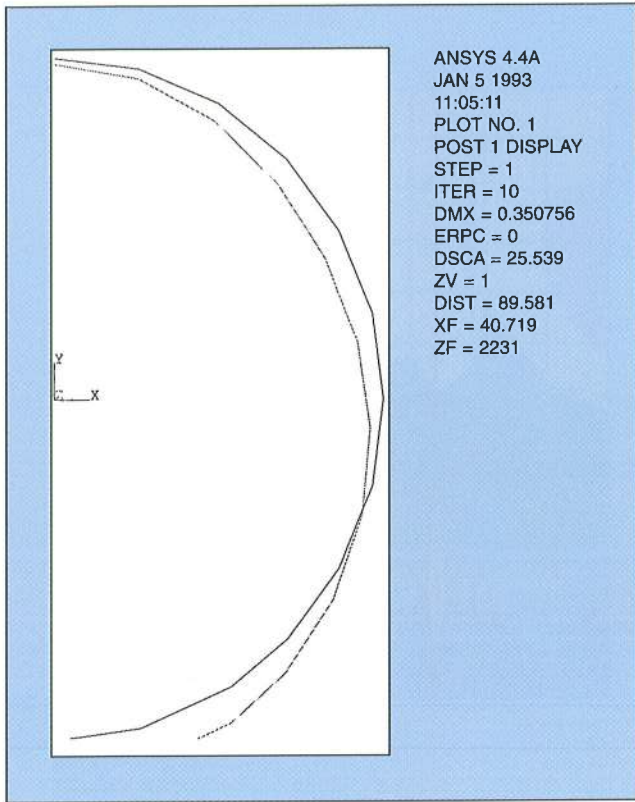


Figure 8. Shell deformation at the centre of the kiln, worst case condition.

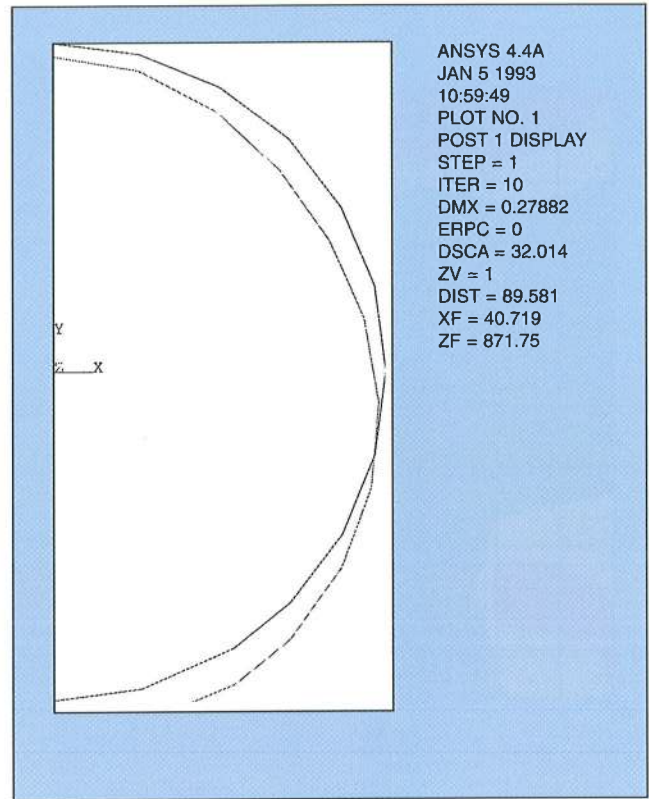


Figure 9. Shell deformation at the centre of the kiln, normal operating condition.

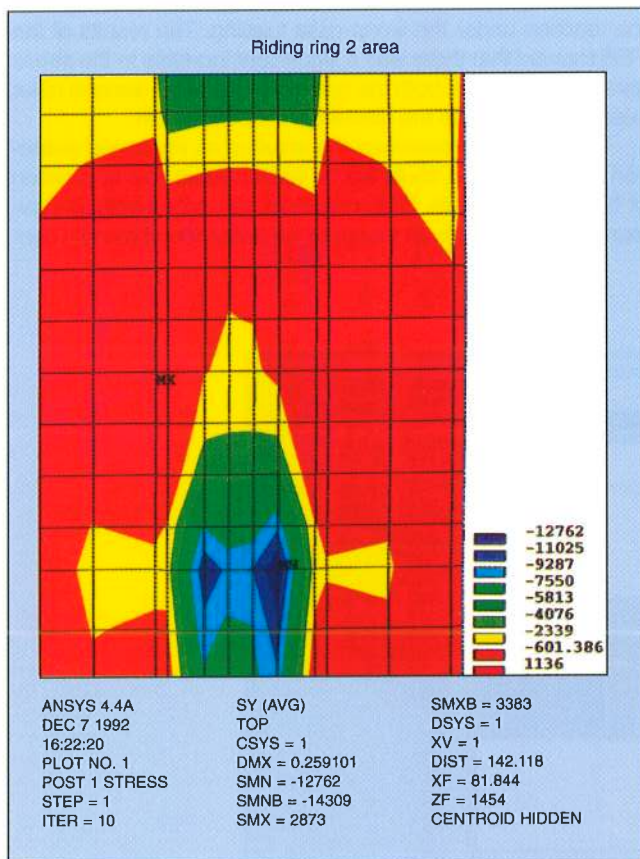


Figure 10. Outside circumferential shell stress,  $S_y$ , at riding ring no. 2 area.

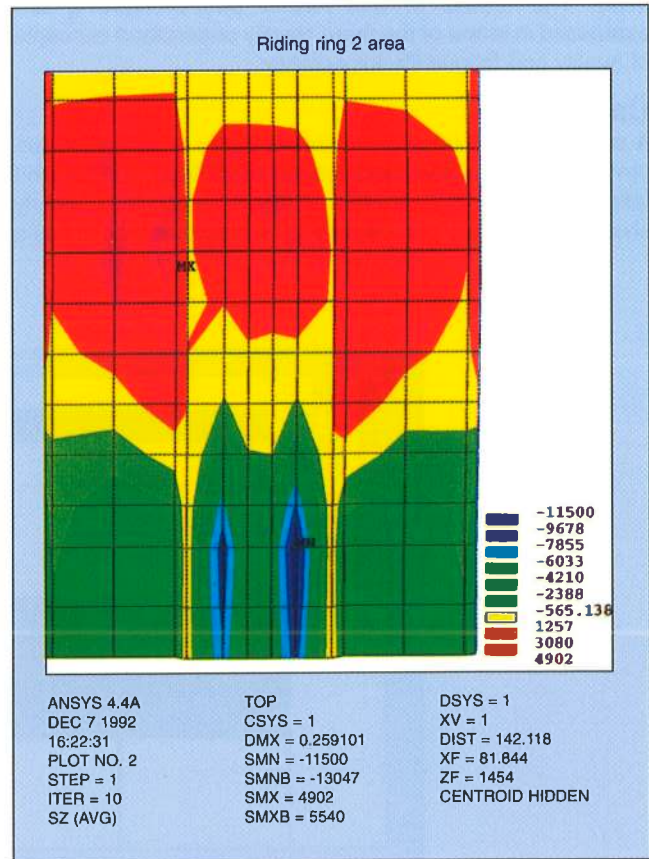


Figure 11. Outside axial shell stress,  $S_z$ , at riding ring no. 2 area.

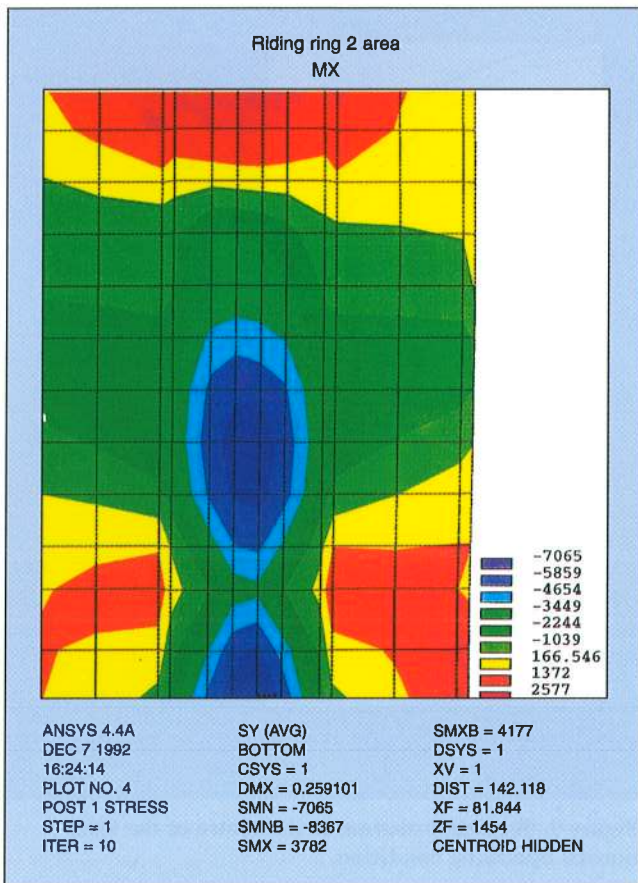


Figure 12. Inside circumferential shell stress,  $S_y$ , at riding no. 2 area.

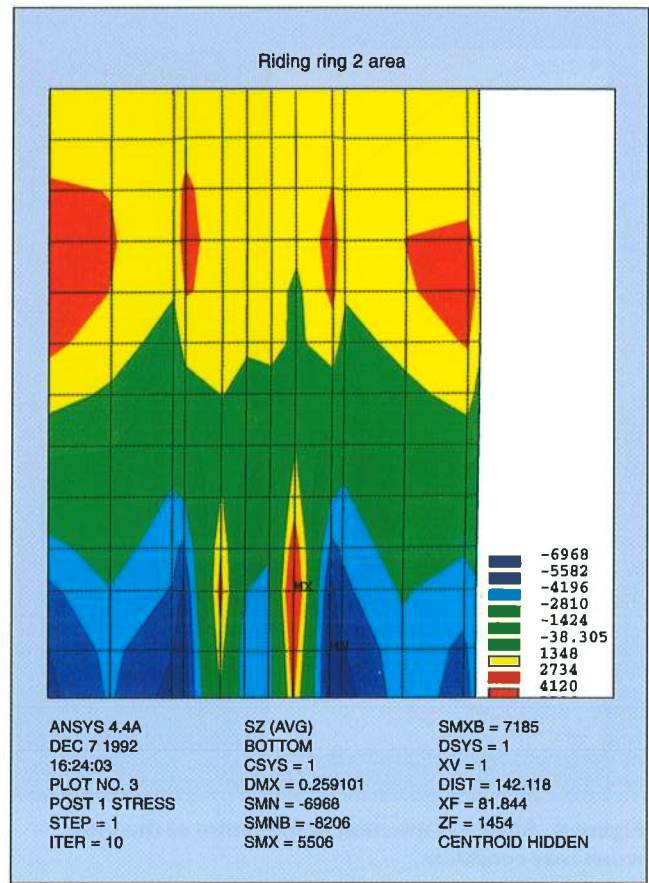


Figure 13. Inside axial shell stress,  $S_z$ , at riding ring no. 2 area.

which utilize the FEA output stress levels as their inputs are used. The results of this further post-processing are expressed in terms of the more readily understood concepts of ovality and fatigue life expectancy.

### Case study

A summary and charts from this particular investigation are provided because the fundamental advantage of FEA and fatigue analysis over traditional beam analysis is clearly shown. The primary purpose of this investigation was to find a

possible cause for a reoccurring bearing failure. The results of the beam analysis showed a rather insignificant increase in the reaction under the worst-case loading. The results of the FEA showed that there was a significant increase in the stress level at one edge of both the tyre and shell at the second roller support station from the discharge end of the kiln.

This stress increase was the result of an increased deflection in the shell that could not be seen through the application of the beam analysis. Beam analysis can only predict behaviour at the centerline. In this case no deflection at the kiln cen-

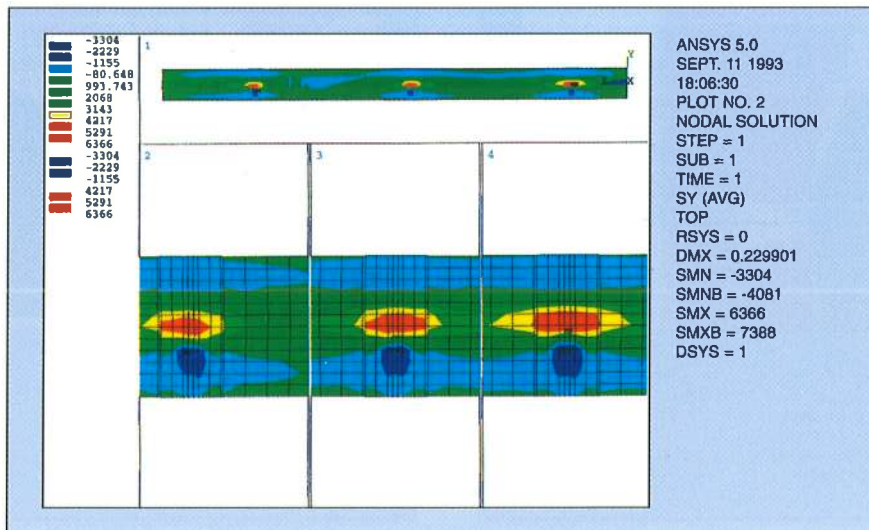


Figure 14. Circumferential stress at outside surface of shell.

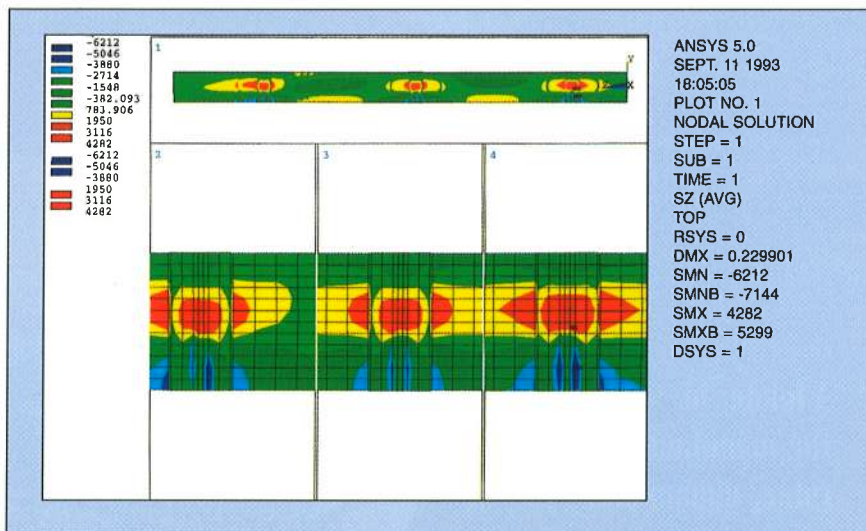


Figure 15. Axial stress at outside surface of shell.

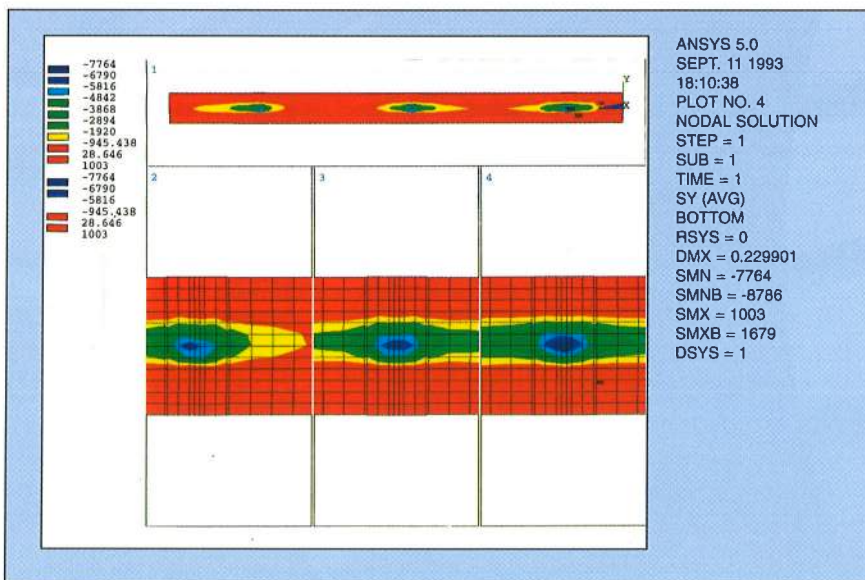


Figure 16. Circumferential stress at inside surface of shell.

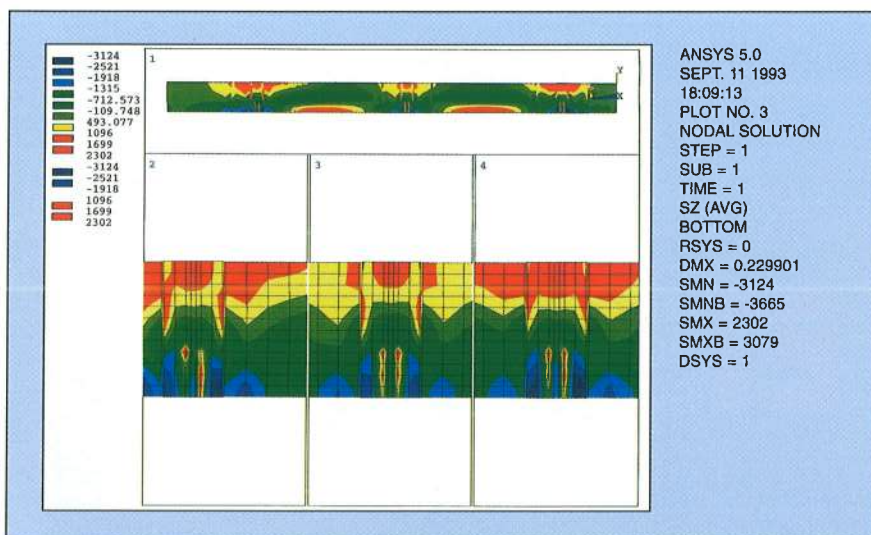


Figure 17. Axial stress at inside surface of shell.

terline was reported to exist in the beam analysis due to the proximity of the support. Investigation using FEA and fatigue analysis showed not only this stress increase, but also pointed out the existence of a potentially larger problem.

It was observed that, under the worst case loading condition, there are several locations where the alternating stresses are higher than 6 KSI (the highest is 7.36 KSI). Figures 4 to 13 show the plots of the shell stresses, and the ring and shell deformations at pier 2. Under this worst case loading condition, the following conclusions were reached. Fatigue cracking would be expected at these locations within a period of one to four years. Failures should occur on a worst case first basis, and that in some cases the cracks would propagate from the inside of the shell out.

The customer thought this was a pretty bold prediction. No further investigation regarding this potential problem was solicited. Oddly enough almost to the anniversary date of the report A-C Equipment Services were asked to dispatch a service representative to assist with some repairs. Upon arrival the following morning he reported that an extensive crack network had developed at the weld joint just downhill of tyre number 2. Fortunately the customer was prepared for this eventuality, narrowly averting the catastrophic consequences of a failure similar to the one shown in Figure 1.

### Conclusion

The purpose of this article is not to second guess the designers and engineers who have preceded us, but rather to introduce a relatively new and misunderstood tool for consideration. FEA and FMA can provide real and understandable results regarding the structural integrity and remaining life in existing kiln structures. These analyses can address concerns regarding the possibility of increased production in terms that can be easily understood. Design modifications can be optimized to maximize life expectancy. Effect of misalignment can be evaluated. It is even possible to simulate intentional misalignments and evaluate the effect on the reaction forces and shell stresses at adjacent parts of the structure. Figures 14 to 17 show the balance that can be achieved in a kiln design that utilizes the optimization techniques that are made possible by FEA and FMA. A-C Equipment Services, as providers to the cement industry, are constantly challenged to provide increased production and improved equipment availability. FEA and FMA are two of the tools required to meet these challenges.

# Fabrication

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