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STRESS ANALYSIS USING ACTUAL COKE DRUM BULGE PROFILES

A CASE STUDY

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Prepared for presentation at the AIChE 2000 Spring National Meeting, Atlanta, GA, March 5-9, 2000, Advances in Coking session

Abstract

Delayed coke drums are operated under severe conditions of cyclic heating and forced cooling that apply repetitive thermal stresses to the drum walls. It has been long recognized that the ultimate failure mechanism for coke drums is weld cracking due to low cycle fatigue caused by these thermal stresses. It is also known that coke drums distort and bulge in service and that these bulges can be used as pointers to potential weld failure areas.

CIA Inspection operates a laser profiling service which locates and measures bulge areas in coke drums. Consistent and accurate measurement of surface deformities has allowed operators to zero in on areas of concern, but it has not been able to quantify the impact of bulges on remaining drum life. CIAI has now developed a method for applying finite element modeling tools to the laser-scanned profiles of coke

drums to evaluate the stress concentrations caused by local distortions. A load model representing the effects of cover gas pressure, hydrostatic head of the coke, and the thermal loads imposed during the quench cycle is applied to the finite element model.

A case study of a coke drum which experienced a through-wall weld crack is presented. The FEM analysis of the measured drum distortions shows a local doubling of axial stress in the area of the weld crack which would have greatly reduced the fatigue life of the weld material in that area.

Future enhancements to the stress analysis model, including weld design inputs and the application of non-uniform thermal loads, will improve the ability to quantify the impact of coke drum bulges and, ultimately, to predict failures.

1 INTRODUCTION

Delayed coking is an important part of heavy oil upgrading operations. As such, the reliability and longevity of delayed coke drums is critical to efficient and economic operation of many refineries.

Delayed coke drums are operated under severe conditions of cyclic heating and forced cooling that apply repetitive ratcheting type thermal stresses to the drum walls. Furthermore, many operators have been pushing up production throughput by significantly reducing coker switch cycle times. This trend, which requires shorter heat-up and quench times, results in the application of higher thermal stresses to the coke drums and can potentially lead to earlier failures.

This paper reviews current coke drum inspection philosophies and presents some new developments aimed at better prediction of coke drum failures. The inspection and modeling tools that have been developed are used to identify the stress concentrations caused by distortion and bulging in a coke drum. Stress risers are identified, ranked and related back to the drum weldment pattern so that the owners of the vessel can react in more a pro-active fashion.

A case study is presented detailing how the measurement and stress modeling of a coke drum surface profile was applied to a drum where a through-wall crack had occurred.

2 COKE DRUM DESIGN, FAILURES AND INSPECTION PRACTICES

2.1 Coke Drum Design

Delayed coke drums are typically designed and built to the ASME “Boiler and Pressure Vessel Code” Section VIII, Division I. They are designed for the pressures resulting from a pressurized cover gas (typically 60 psi) and the hydrostatic pressure due to the weight of the coke charge. The vessel material and wall thickness is selected based on the calculated pressures at the elevated temperatures expected in operation. Even though they are used in a temperature cycling duty, coke drums are not generally designed to fatigue criteria – although recent designs typically avoid details (e.g., welded insulation support rings, attachment lugs, pad reinforced nozzles, etc.) which have been found to lead to high temperature-induced stress concentrations points.

This design method usually results in the cylindrical vessel walls being fabricated from ring sections, or "courses", with plate thicknesses decreasing from the bottommost course to the topmost course. While early coke drums were fabricated from carbon steel, and later from C 1/2Mo alloys, most modern drums are made from 1Cr-1/2Mo or 1 1/4Cr-1/2Mo low alloy steels. Wall thicknesses, including the usual 410S or 405 stainless steel cladding on the inside surface, vary from less then ¾" to over 1½" thick (i.e., relatively thin walls for vessels ranging from 18 to 27 feet in diameter and 60 to 85 feet high).

It has been long recognized that the ultimate failure mechanism for coke drums is crack initiation in plate-plate welds due to low cycle fatigue.[(1),(2)] Few coke drums have survived past 7,000 coking cycles without weld failures. However, since a typical coke drum has between 500 and 1000 feet of inter-plate welds, 100% inspection of welds for incipient cracking has never been practical. Fortunately, the normal operating metal temperatures keep the drums in a ductile range thus resulting in a leak-before-break failure mode in most cases. Even though leak-before-break tends to avoid more catastrophic failures, these leak incident result in costly shut downs and repair requirements

It is also known that coke drums distort as a result of the extreme thermal cycling that is part of their fill-quench-empty-reheat-fill cycle. [(3)] Typically these distortions appear as circumferential "bulges" running part or all the way around the circumference of the drum, often near a circumferential course weld. A number of coke drum owners have used the incidence of drum wall distortions as pointers to possible weld failure areas. Bulges are treated as indications of stress concentrations and welds in these areas are monitored in the hopes of identifying cracks before they become through-wall failures, thus improving overall vessel reliability.

2.2 Traditional Inspection Methods

Early manual inspection methods for locating and characterizing drum wall distortion were performed during vessel turnarounds. After scaffolding the inside of the vessel, a team of inspectors would perform an internal visual and dimensional inspection to determine the state of the coke drum. Because of the need to enter the vessel, inspections of this type were performed infrequently during major unit turnarounds that typically occurred once every 4 years. Taking manual dimensional measurements was laborious, prone to inaccuracy, and impractical for mapping more than local areas of the drum wall.

2.3 Background of CIA Inspection Service

CIA Inspection (herein referred to as CIAI) developed and operates a specialized laser surface profiling system designed to internally inspect coke drums during the short time period between coke cutting and refilling. The company started performing contract inspections five years ago and to date has performed over 200 internal inspections of delayed coke drums. CIAI's inspection system uses a remote sensor package deployed from the coke drum's drill stem as shown in Figure 1:

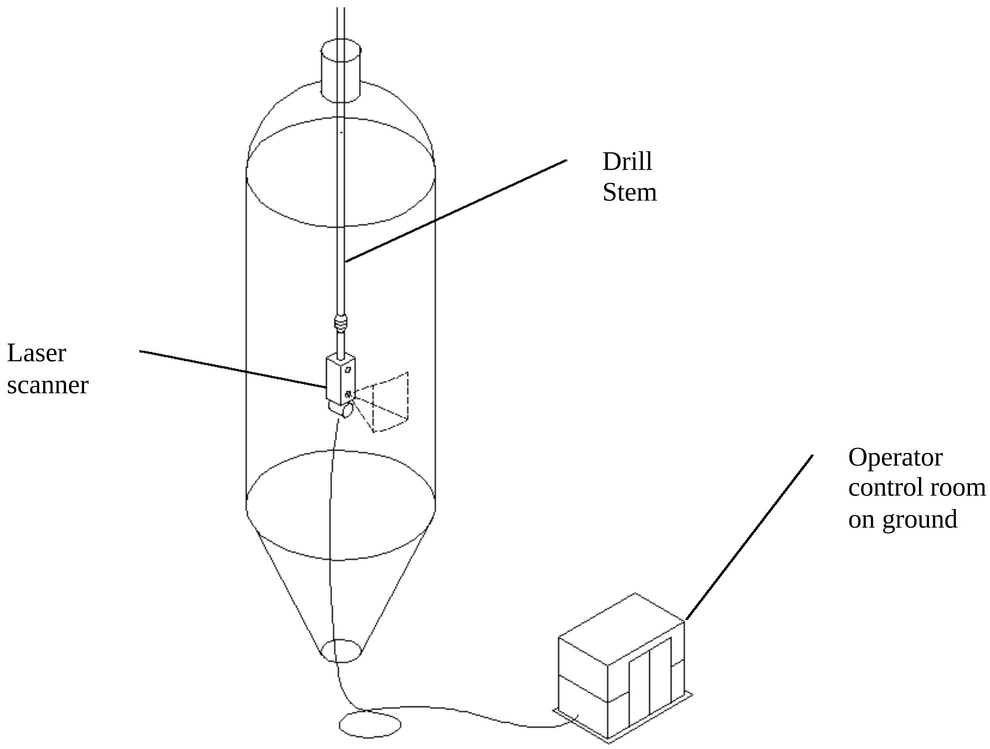

Figure 1: Coke Drum Inspection System with Laser Profiler

A color video camera with zoom lens permits a detailed remote visual inspection of the inside of the drum capable of identifying surface flaws such as cladding defects or weld cracks.

A scanning laser range finder produces an accurate and dense surface profile of the entire inside surface of the vertical walls of the drum. The capabilities of the laser scanner has elevated surface profiling from an occasionally-used qualitative method to a much more useful tool which:

- profiles the entire inside surface of the vertical drum walls on a 1" X 1" grid. This ensures that no deformations are "missed"
- measures depths of deformations to 1/8" accuracy
- measures drum ovality as well as local bulges and wrinkles
- measures repeatably and therefore provides a means of accurately comparing initial scans with subsequent inspections.

The quality of the surface profile data produced by CIAI's inspection system has allowed coke drum operators to:

- compare the degree of deformity among their different drums, thereby identifying which drums are likely to require more inspection effort
- focus further inspection efforts on welds near deformed areas
- compare the change in drum deformities over time through the repeat use of CIA's inspection system

This use of CIAI's automated inspection service over the past five years has been particularly timely as many operators have been pushing up production throughput by reducing coker cycle times. By "benchmarking" a coke drum's surface profile before changing cycles times and then rechecking the profile after several hundred cycles at the new cycling rate, operators can determine whether the cycle time change has led to an increase in drum bulging. This information can then be used to formulate pro-active inspection plans to maintain vessel reliability while operating at increased throughput.

3 ADDITION OF STRESS ANALYSIS CAPABILITY

3.1 Modeling Actual Surface Profiles

While the consistent and accurate measurement of surface deformities has allowed operators to compare their drums with typical industry averages, and zero in on areas of concern, it has not been able to answer the question: "How bad is this bulge?". In particular, it has not been possible to quantitatively predict what the impact of a surface deformity would be on the remaining life of the drum or even to determine how the deformity is affecting the stresses applied to the drum.

CIAI is addressing this concern by developing methods for applying sophisticated finite element modeling tools to the measured profiles of coke drums. A number of finite element analyses have already been performed on coke drum models. These studies have modeled the effects of :

- local temperature differences during quench cycles as measured by thermocouples
- local strains during quench cycles as measured by strain gauges

In all cases, they have used the coke drum's as-designed profile as the basis of the finite element model. However, finite element modeling software can readily evaluate the stress concentrations caused by local distortions if these actual profiles can be included in the model.

Along with SRT - Structural Reliability Technology in Boulder, Colorado, CIAI has developed sophisticated software tools to generate finite element meshes directly from actual coke drum profile information captured by the laser scan data. The inside profile of the drum is extracted directly from CIAI's dense 1" X 1" laser range scan data. It is essential to make use of such closely spaced surface dimensions, as the stress concentrations around deformations are very localized and would not show up with a larger grid size.

The meshes are generated as full "brick" elements which model the varying thickness of the drum wall as well as the inside surface profile. A coefficient of thermal expansion for the drum wall material of 7 X 10^{-6} in/in (typical for steel at 350^0F to 400^0F), a modulus of elasticity, E, of 30 X 10^6 psi, and a Poisson ratio of 0.30 is used.

These meshes are then used to perform finite element analyses of the stresses and strains in the coke drum walls under various loading conditions.

3.2 Load Models

A load model has been developed which simulates a typical "worst case" combination of coke drum loads, namely:

- 40 psi cover gas pressure,
- the static head of a coke fill,
- and the thermal shock wave moving up the drum as it is quenched

To model the cover gas pressure, the equivalent axial stress is applied at the top of the mesh for the analysis region. A hydrostatic pressure term is included to model the weight of the coke charge at each elevation in the drum.

To simulate the thermal effects of the addition of quench water, the upper part of the FEM analysis region is set to a uniform 800^0F. The lower portion of the analysis region is then set to 300^0F. There is a transition layer, five inches high, from the hot to cool temperature regions (a temperature gradient of 100^0F per inch). The resulting thermal gradient is sufficient to produce local stresses above the material yield in the drum wall. Since permanent bulging of a coke drum implies that the drum wall has yielded, this is a fair starting assumption.

This quenching profile is moved up the analysis region over 10 analysis steps to simulate the cooling fluid filling the vessel. The quenching profile has a uniform height across the analysis region at each step.

3.3 Extracting Results from the Model

When the load model is applied to the profile mesh, all six primary components of stress and strain are generated. The particular components of interest in coke drums are the axial stress and strain as they are the components that lead to crack initiation and growth in circumferential welds. Furthermore, when a thermal "wave" load is applied, the difference between minimum and maximum axial stress at a point on the drum is directly related to the low-cycle fatigue life of the circumferential welds.(4) This "delta axial stress" is, therefore, the stress component of most interest.

The delta axial stress for each finite element node is determined by finding the maximum and minimum axial stress as the thermal wave load model is moved up through the analysis region. If the minimum stress value that was found was positive, then the minimum stress is set to zero to cover the initial stress-free condition with no pressure or thermal loads. The results are plotted for each finite element node using a 3-D false color viewer.

4 CASE STUDY

CIAI recently applied the new stress modeling capability described above to a coke drum where a through-wall crack had occurred in a circumferential weld.

4.1 Coke Drum Description

The drum in question was manufactured in the early 1990's and is representative of modern delayed coke drum construction. It is 22' in diameter and 66' high from tangent to tangent and is fabricated from 1 1/4Cr-1/2Mo low alloy steel. The bottom three courses of the drum, comprising the bottom 24' of the drum wall, are fabricated from 1” thick shell plate clad with 5/64” thick 410S stainless steel. The next three courses, covering the centre 24’ of the drum wall, are fabricated from 7/8” thick shell plate with the same cladding. This results in a diameter/wall thickness ratio of 264 in/in in the bottom three courses, which is fairly typical.

The drum is operated on an 18 hour switch cycle and had accumulated approximately 1200 preheat-fill-quench-cut cycles at the time of its first laser profile scan.

4.2 Laser Profile Results

CIAI performed a laser profile scan on this coke drum in 1998. The resulting ID profile identified a number of deformities in the drum, as shown in Figure 2. The predominant deformities were circumferential bulges mainly clustered in the 4th course from the bottom, i.e. the lowest course fabricated from 7/8” thick plate. Of particular interest were several bulges lying on the course four-to-course five circumferential weld.

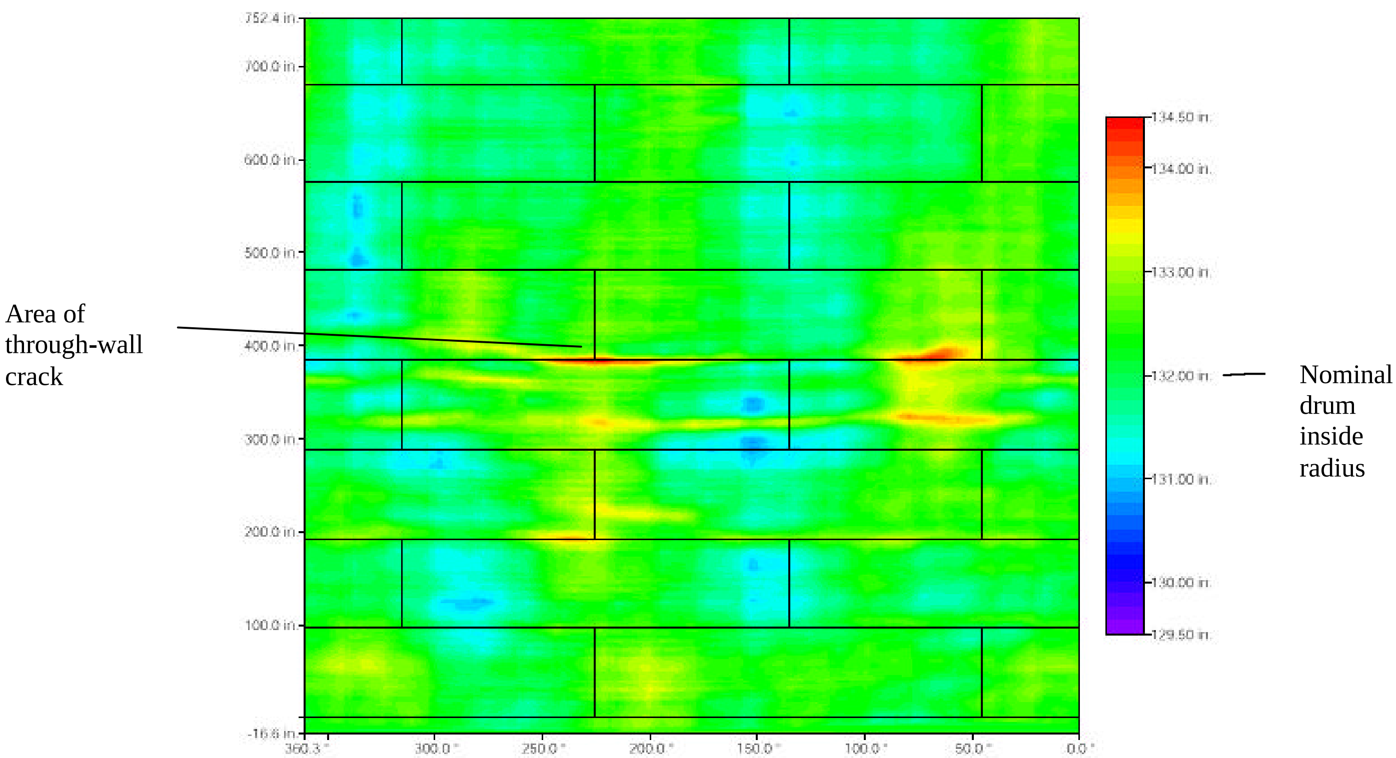

Figure 2: Drum Surface Profile Map

A vertical cross-section through the ID profile of the bulge at the intersection of the course four-to-course five weld and the vertical weld at 225^0 azimuth is shown in Figure 3. Note that the horizontal scale on Figure 3, representing the drum radius, is greatly exaggerated compared to the vertical representing height on the drum wall. In fact the maximum bulge depth is only 1 ½% of average drum radius and would barely be discernable by eye.

Approximately six months subsequent to the laser scan, the drum suffered at through-wall crack in the circumferential weld in this area.

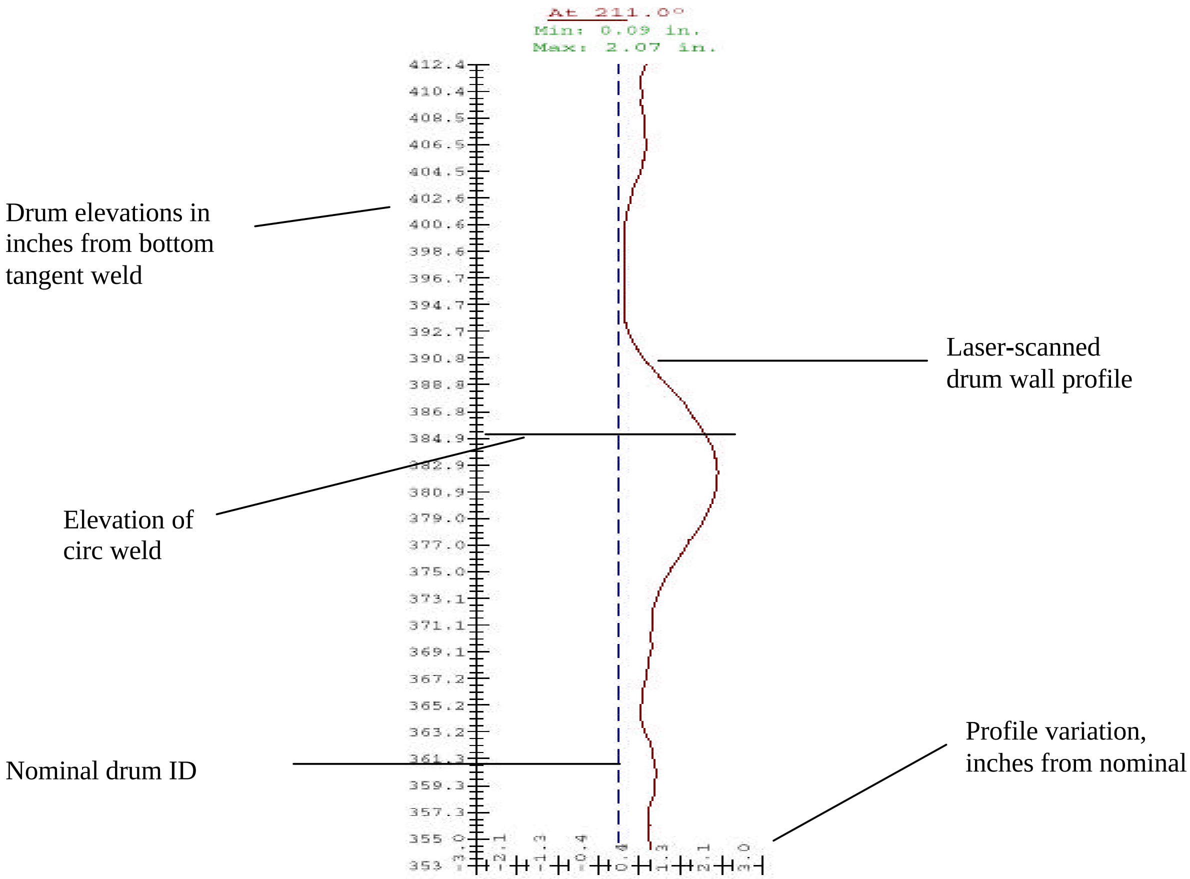

Figure 3: Cross Section Through ID Profile at Bulge

4.3 Stress Analysis Results

The coke drum in this case study was analyzed using the finite element analysis procedure outlined above. Four different regions of the coke drum vertical walls were analyzed, covering the main areas of bulging, as follows:

Region	Azimuth angle (deg.)	Height range (inches)
1	15 to 105	290 to 420
2	**150 to 330**	**340 to 420**
3	95 to 185	250 to 370
4	185 to 275	250 to 370

It should be noted that Region 2 includes the weld intersection where the through-wall crack occurred on this drum.

For each region, a finite element mesh was created from the laser scan data and the resulting model was subjected to a combination of hydrostatic and internal pressure loads and a varying temperature load as outlined in Section 3.2. In general, the highest "delta axial stress" in undeformed areas of the drum wall was found to be on the order of 30,000 psi. However, much higher local delta axial stresses were found in bulge areas, ranging up to and over twice the maximum in unbulged areas:

Region	Maximum delta axial stress in the analysis region (psi)
1	64097
2	**62984**
3	60035
4	61101

It was particularly interesting to note that the peak stresses occurred at the "shoulders" of the bulge, i.e. above and below the maximum peak of the bulge, where the radius of curvature is the greatest. Figure 4 shows a typical output of the stress analysis, false colored to highlight high (red) and low (green) axial stress areas.

Several of these high axial stress areas overlap the circumferential weld between the 4th and 5th course and it was in that particular weld location that the through-wall crack had occurred.

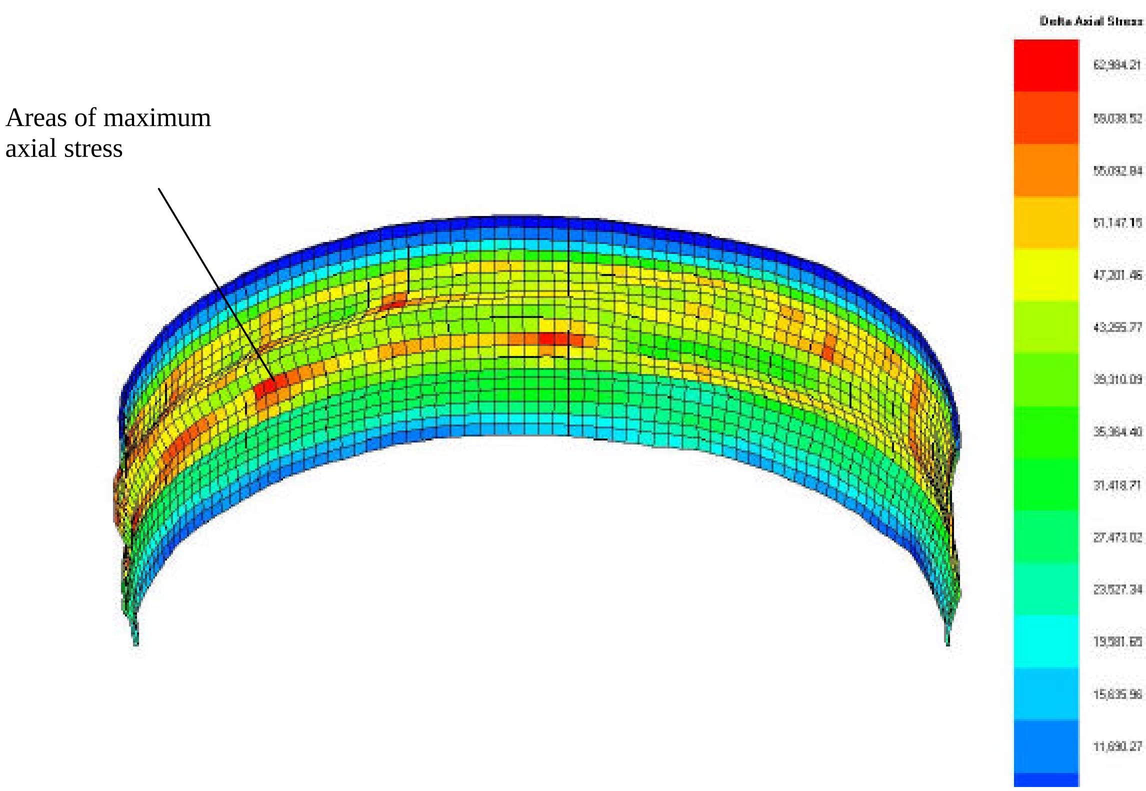

Figure 4: Delta Axial Stress Map – Region 2

5 CONCLUSIONS

5.1 The Effect of Drum Wall Deformation on Fatigue Stresses and Drum Life

The above study shows a case where the introduction of apparently small bulges, representing only about 1½ % radial growth in the drum, can lead to a drastic increase in localized axial cyclic stresses. For the hypothetical loading conditions used in the case study, stresses caused by cyclical loading of the local distorted area showed a 100% increase over the surrounding area. The type and magnitude of the distortions analyzed in this study are not uncommon in the large database of drums scanned by CIAI, especially among 1¼ % chrome drums.

It is also noted that the stress concentrations resulting from drum distortions are extremely localized and could not be properly analyzed without the use of a very dense array of surface profile measurements. More coarse surveys of the drum wall profile would not resolve the full shape of the bulge, and therefore the stress peaks associated with the shoulders of the bulge or other unique shape features would not be accurately identified.

Since the fatigue life of steel decreases with the cube of the fatigue stress, a doubling in fatigue stress results in a reduction of fatigue life by a factor of eight. As the above analysis highlights, local and relatively minor distortions can have a serious impact on the time to initiation of weld cracking if the deformities are near circumferential welds.

5.2 Usefulness of Stress Analysis as a Tool for Evaluating Coke Drums

Recognizing the impact that drum distortions have on stress concentrations and fatigue life, it is clear that operators of coke drums can benefit through the long term monitoring of their coke drum surface profile. Identification and tracking of vessel profile combined with an engineering stress analysis can be a useful measure of long term reliability of coke drums.

This paper discusses CIAI's preliminary efforts at developing an analysis routine to interpret the impact of vessel profile on operating performance. The encouraging indications of the above case study suggest that this sort of modeling could be used in a predictive fashion to aid operators in answering the main question – when and where will coke drums fail. Some future enhancements to the stress analysis model will include:

- the ability to factor in the impact of the weld design
- application of non-uniform thermal loads to more closely simulate the real world condition of coke channeling of the quench water to the drum wall.

Continued input from coke drum operators on actual failure incidence combined with accurate vessel profile information along with the refinement of the current stress analysis model will improve it's ability to highlight failure prone areas and, ultimately, to predict failure.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the help of T. L. Anderson of Structural Reliability Technology, and G. G. Karcher, Consulting Engineer, in the preparation of this paper.

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