Finite Element Analysis of a Fluid Catalytic Cracking Reactor Cyclone

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Abstract

The BP Kwinana oil refining process includes a Residue Cracking Unit (RCU). In July 2004 problems were first identified within the process. Subsequent investigations revealed significant structural damage to the two reactor cyclones. Finite element modelling was used to analyse the structure and identify the most significant damage mechanisms. The analysis confirmed the thermal constraint during shutdowns, due to coke deposition, to be the primary cause of the structural failure. The modelling showed the coke restraint was likely to result in significant weld failure on the cyclone roof due to excessive throat stresses. This situation was found to be further exaggerated by the use of austenitic stainless steel in the construction of the reactor cyclones. Other damage mechanisms considered included fatigue and static overloading. However, these were not found to have a significant effect on the structure. The project has highlighted the effects of coke deposition on the reliability of the reactor cyclones. The minimization of coke growth from a design perspective and the removal of coke deposits during shutdowns have been identified as key factors in addressing this problem.

1. Introduction

BP's Kwinana refinery has been operating since 1955 and is Western Australia's only refinery. The refinery is one of the most modern in the southern hemisphere and has a capacity of 138,000 barrels of crude oil per day making it the largest in Australia (BP Australia 2007). This refinery produces a range of products including petrol, diesel, aviation fuel, bitumen and LPG. An integral part of the oil refinery's conversion process is the Residue Cracking Unit (RCU).

The RCU uses Fluidized Catalytic Cracking (FCC) to break up long-chained hydrocarbon molecules into shorter and more valuable products. The FCC process uses a high temperature reaction assisted by a catalyst to promote the cracking reaction. A byproduct of the reaction is coke which is laid down on the catalyst. The catalyst is separated from the cracked products by cyclonic separation and the coke burnt off during the continuous catalyst regeneration process. The RCU operating at BP Kwinana utilizes two reactor cyclones.

2. Background

The RCU at BP Kwinana has been operating since 1987 with the reactor cyclones last being replaced in 1998. The first indication that there was a problem was when catalyst carryover to the fractionator and slurry system occurred. Catalyst carryover problems began in July 2004 and got progressively worse over the next four months. Catalyst carryover caused erosion of the slurry pumps reducing service life from 18 months to just 1 month. A failure analysis identified problems within the RCU which resulted in the catalyst carry-over (Brook 2006).

The initial prognosis was that a damaged Riser Termination Device (RTD) was the cause of the process problems. However, subsequent repairs did not lead to a reduction in catalyst carry-over.

Further investigation suspected failure of the welds on the reactor cyclones may be responsible for the problems (Brook 2006).

2.1. Cyclone Damage

In 2006 the RCU was shutdown and an inspection revealed severe coke growth on the cyclone roofs. Coking is a characteristic problem in all FCC units and can be attributed to the condensation of hydrocarbon vapors (Sadeghbeigi 2000). Visually the coke formation on the east and west cyclones appeared to be similar. After the coke deposits were removed mechanically, widespread weld failure and plate fracture was identified on the cyclone structures (Brook 2006).

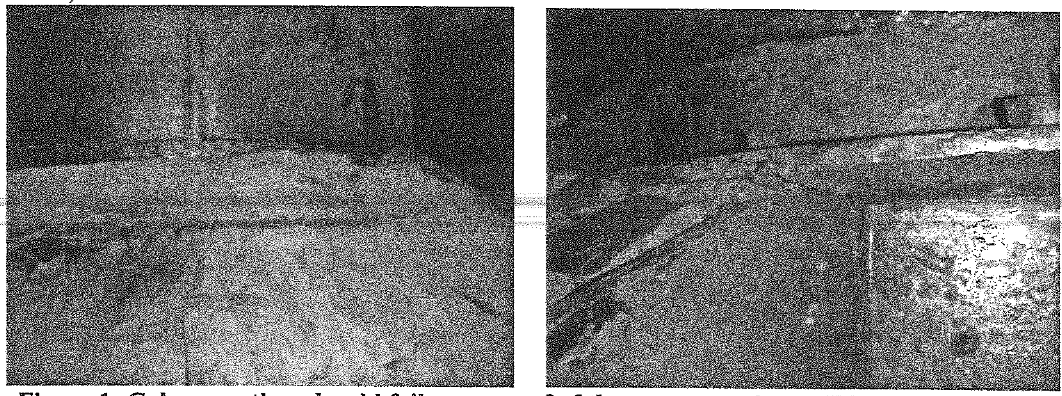

Figure 1: Coke growth and weld failure on roof of the reactor cyclones (BP Kwinana 2006).

The weld failure was predominantly located on the cyclone roof and was uniformly distributed around the cyclone's central axis. Weld failure was evident between the cyclone roof, compression ring and stiffener plates. Many of the stiffener plates also had cracks initiating at the weld toe and migrating into the parent metal. Interestingly, the failure mechanisms in the two cyclones were slightly different. The east cyclone showed significant weld failure whilst the west cyclone had predominantly stiffener plate fracture.

2.2. Failure Analysis

A Root Cause Failure Analysis (RCFA) was conducted by technical staff at BP Kwinana to determine which factors were most likely to have caused the cyclone damage. Mechanical cracking due to thermal constraint was considered the most likely cause of cyclone failure. The design is susceptible to coke growth between the cyclone roof and compression ring. The coke build up provides constraint and consequently thermally induced stresses when the vessel is shutdown (Sweetman 2006). The difference in thermal expansion between the cyclone and coke was thought to be exacerbated by the use of austenitic stainless steel.

Cyclone fabrication was also identified as contributing to the failure (Sweetman 2006). Inspection revealed the cyclones were not fabricated as per the original designer's specifications. This resulted in undersize welds and plate thickness. Inspection revealed the welds on the east cyclone to be smaller than the corresponding welds on the west cyclone (Cornish 2006).

Carburization of the stainless steel was also proposed as a possible contributor (BP Kwinana 2006). The presence of carbonaceous compounds, such as coke, coupled with the proper conditions, can lead to carburizing activity. However, material testing showed carburization to be present but not at a significant level or depth (Cornish 2006).

Although mechanical overload was considered, it was not thought to be a major factor in cyclone failure (BP Kwinana 2006). The static weight of the cyclone was safely below the maximum emergency design load. However, it is believed that the dynamic loading from the catalyst flow could be responsible for failure. This situation would be further exaggerated by the loss of the dipleg brace and hence lessening of restraint against lateral loads.

The thermal loading on its own was not considered to be the main cause of the damage (BP Kwinana 2006). The cyclone temperature is quite uniform as the internal and external faces are exposed to the same fluid temperature. Service temperatures are not high enough to significantly weaken the material and thermal transients are not severe. The lack of visible refractory damage supports this argument.

3. Finite Element Methods

The finite element method is a numerical approach that can be used to solve problems of engineering and mathematical physics. The fundamental areas solvable by finite element methods include structural stress analysis, heat transfer, electromagnetism, fluid flow and mass transport.

Finite element techniques are tremendously useful for analysis of structures. The method provides a practical approach to predicting stresses, load paths and deflections in loaded structures. Finite element analysis (FEA) provides a wide range of simulation options whilst allowing the complexity of the model to be controlled (Logan 2002). This technique makes it possible to evaluate detailed and complex structures, like the reactor cyclones, and the effects of specific loading conditions. The use of finite element methods is also advantageous because it provides an easy way to model the coke growth loading by using different material models.

A significant part of this project includes analysing the weld design and failures. Finite element analysis allows the loads carried through the joints to be calculated (Weaver 1999). These results can be easily manipulated to evaluate the weld throat stresses and size requirements. This would be extremely difficult using classical analysis due to the complexity of the structure.

4. Finite Element Modelling

4.3. Static Loading

The initial analysis involved analysing the basic design of the structure under normal operating conditions and loadings. A simple model was used at this conceptual stage to understand the behaviour of the structure, stress levels and load transfer.

The results showed that the maximum stress through the shells was safely below the design stress for grade 347H stainless steel. The maximum stress is in the stiffener plate and is approximately 22MPa which is well below design stress (99 MPa) for grade 347H stainless steel at the reactor operating temperature (AS1210 Table 3.3.1(B)). This represents a safety factor of 4.5 when an emergency catalyst load is considered.

4.4. Coke Growth Loading

Coking occurs frequently within FCC units and often forms on the reactor walls, dome, nozzle, cyclones and transfer line between the reactor and main fractionator. The roofs of the reactor cyclones are also susceptible to coke formation due to the stagnant vapor flow in these areas. The design of the BP Kwinana reactor cyclones means they are particularly vulnerable to coke growth between the cyclone roof and compression ring. The large difference in thermal expansion between austenitic stainless steel and coke leads to the constraint of the cyclone structure and consequently induced stresses as the reactor temperature decreases during shutdown.

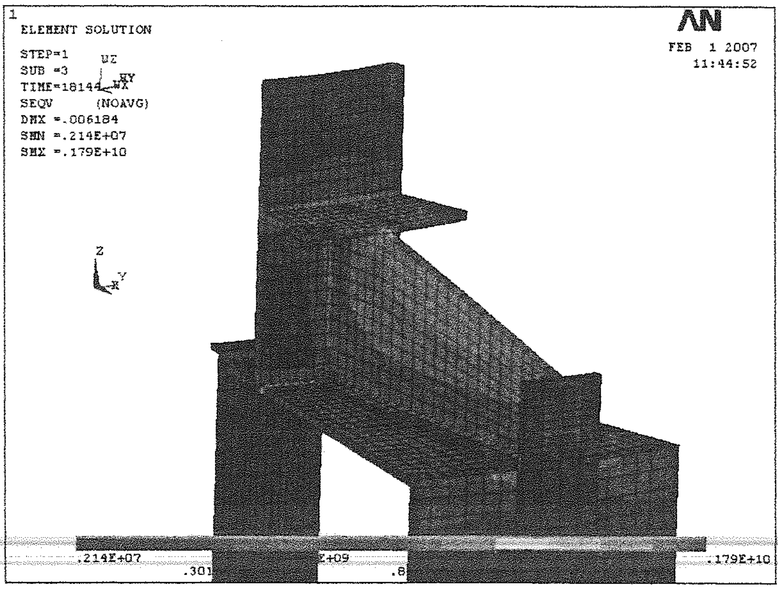

Figure 2: Effects of coke restraint on cyclone roof structure.

The coke deposition on the cyclone roof has a significant effect on the structure. The results of the analysis are shown above in Figure 2. The average stress level in the stiffener plate is approximately 280 MPa which is above the yield strength (263 MPa) of Grade 347H stainless steel at operating temperatures. The level of stress in the cyclone has increased significantly with the presence of the coke growth although the load path is approximately the same. Figure 2 shows that the stiffener plate and compression ring transfer a significant amount of the load and are highly stressed.

4.5. Weld Design Analysis

The welded joints on the roof of the reactor cyclones are double fillet welds. For a fillet weld the majority of the deposited weld material lies outside the silhouette of the joined members resulting in incomplete penetration (Wright 2005, p. 92). This geometry is unfavorable and results in an inherent crack like defect and severe stress concentration.

Weld stress analysis for fillet and partial penetration welds involves comparing the load transmitted through the weld by the minimum throat area and then comparing against the shear allowable for the electrode material. This process can be used to calculate weld and throat size requirements for a given structure.

The weld analysis is concentrated on the gas outlet tube and the joints with the cyclone roof, cyclone and compression ring. The modellings showed the throat stresses for the gas outlet tube and stiffener plate welds to the cyclone roof and compression ring were in excess of the allowable stress. Consequently, the failure of these welds was likely. These results matched the observed weld failures and failure sequence hypothesised by the BP Kwinana technical staff.

The analysis highlighted the significant effects that coke growth has on the cyclone structure. Hence, from a design and maintenance perspective, the control of coking is a key consideration within any FCC unit.

4.6. Fracture Mechanics

The results so far identify mechanical stress, arising from the restraint due to the coke, as being the primary cause of cyclone failure. The coke growth leads to excessive weld throat stresses and consequent weld failure. During the 2006 shutdown, significant cracking of the stiffener plates was observed on the cyclone roof. The cracks propagated from the weld attaching the stiffener plate to the compression ring. Examination of the fracture surfaces on the failed stiffener plates showed visible necking characteristic of a tensile failure mechanism.

Finite element analysis was used to model the effects of the cracked stiffener plates. A fracture mechanics based approach was used to develop a better understanding of the basic initiation and growth of cracks in the stiffener plates and the effects on the cyclone structure.

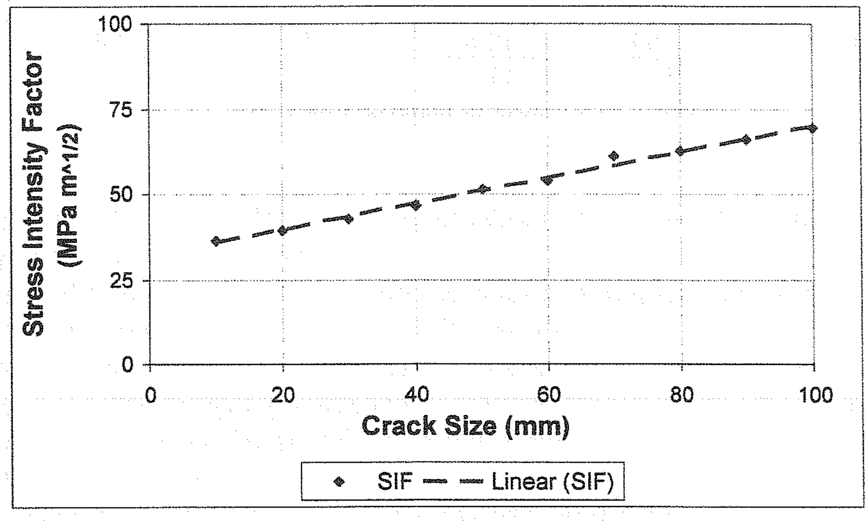

Figure 3 Effects of crack size on stress intensity factor (SIF).

The finite element results predict a stress intensity factor of approximately 50 MPa$\sqrt{m}$ for a 50mm crack. A 50mm crack was the largest crack identified on the stiffener plates of the actual reactor cyclones. The model also shows that in a scenario where the crack was able to propagate further, increasing in length to 100mm, the stress intensity factor would increase to approximately 70 MPa$\sqrt{m}$ (Figure 3).

The plain strain fracture toughness for austenitic stainless steel is approximately 100 MPa $\sqrt{m}$ (Hallemans 2000). The calculated stress intensity factors are well below the material fracture toughness values. Consequently the cracking evident in the stiffener plates has not significantly affected the integrity of the cyclone structure.

4.7. Material Construction

Materials used in the construction of reactor cyclones include various grades of chrome molybdenum (Cr-Mo), stainless (SS) and carbon steels (CS). However, there is no ideal choice as each material has its own relative advantages and disadvantages. The selection must be based upon careful consideration of the process conditions and management of the anticipated damage mechanisms.

Finite element analysis was used to evaluate the effects of the different material properties. The most significant material properties will include the co-efficient of thermal expansion (CTE), elastic modulus and tensile strength. The difference in CTE between the materials is important when considering the constrained thermal expansion arising from the coke growth.

The results from the analysis are summarized below in Table 1. The results show stress varies significantly due to the different thermal properties of the materials. As expected, the chrome molybdenum steels, which have lower CTE values (12.4 -14.6 * μm/m-°C), have the lowest weld throat stresses (226 - 272 MPa). This can be explained by the reduced differential between the thermal expansion properties of the coke and plate material. Conversely, the austenitic stainless steel had the highest stress (341 MPa) as a result of having a higher CTE (18.4 μm/m-°C).

Material	Specification	Grade	CTE (µm/m-°C)	S_u (MPa)	_measured (MPa)	Safety Factor
Carbon Steel	SA 516	70	14.6	483	267	1.8
1Cr-1/2Mo	SA 387	12	14.6	448	272	1.6
5Cr-1Mo	SA 387	5	13.5	517	249	2.1
9Cr-1Mo	SA 387	91	12.4	586	226	2.6
Austenitic SS	SA 240	347	18.5	517	341	1.5

Table 1 FEA results of material comparison.

5. Conclusion

Finite element analysis has been used to model the reactor cyclones and determine the primary cause of failure. This analysis has shown that the coke growth loading is responsible for the cyclone damage. Other damage conditions such as fatigue did not have a significant effect on the cyclones. The high operating temperatures and different thermal expansion properties, between the petroleum coke and austenitic stainless steel, resulted in a thermal constraint problem. The coke growth loading on the cyclone roof resulted in excessively high stresses in the weld throats which lead to widespread weld failure. Furthermore, modelling of various construction materials showed the thermal constraint to be exaggerated by the use of austenitic stainless steel due to its greater co-efficient of thermal expansion. The analysis also showed that the cracking evident in the stiffener plates was unlikely to result in significant structural weakness. However, the modelling showed that the stress concentration, and load transfer, through the stiffener plates meant that the further propagation of these cracks was likely. The outcomes of this investigation have shown that the key to extending cyclone life is the removal of any coke deposits on the reactor cyclones during scheduled shutdown periods.

6. References

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