# Restoration of Coker Structures

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## ABSTRACT

Coker structure is a heavy industrial reinforced concrete construction in a refinery that supports a delayed coking unit, consisting of multiple coke drums, on an elevated platform. The process temperatures inside a coke drum can reach up to 480 °C (900 °F) and thus subject the supporting concrete structure to extreme thermal gradients. Due to these high temperatures in conjunction with mechanical stresses, the areas of concrete surrounding the coke drums deteriorate over a period of time and in most cases before the lifetime of the concrete structure. The deteriorated reinforced concrete elements needs to be addressed before they lose structural capacity which may lead to a structural failure. Thus, it is important to develop an effective repair strategy for the restoration of the Coker structures giving at most importance to the safety during construction and reliability of repairs to extend the lifetime of the structure. A Coke drum can reach up to a weight of $2.7\times10^6$ kg (6000 kips) under its full operating condition. Considering the size of these drums, it is very critical to design a phased repair solution for the repair of Coker structures when they are deteriorated over the course of their service life. A phased repair solution is developed by analyzing the structure by redistribution of drum operational weight and wind force on the drum on to the structure's non-critical members which are repaired in the subsequent phases of construction. The construction of the repair and the effectiveness of the repair to develop the structure's original strength depends on the ability if the repair to transfer the planar stresses between the existing concrete and the new repair material. A repair mechanism to transfer these stresses will be discussed as a part of the best repair approach for concrete sections.

## INTRODUCTION

Coking in a petroleum industry is a method of creating Coke by processing the concentrated carbonaceous sludge that is a residuum from the atmospheric and vacuum distillation of the crude oil. Currently there are 49 delayed coking units that are operating in various petrochemical refineries across the United States. The byproduct of the coking process which is nearly a pure carbon is called Coke, also referred to as Petroleum Coke (Petcoke). Due to its high carbon content, Coke has many applications in electric power plants and other energy producing industries which require a potential source of carbon. The Coking process takes place in a Delayed coking unit of a petroleum refinery where the sludge is heated to a temperature of 510°C (950°F) in a Coker furnace to initiate the cracking of this heavy liquid material and transferred in to coke drums under a pressure of 2.4 atm (20 psig). The hot sludge in the coke drums is thermally cracked for about 16 hours in the coke drum to produce smaller molecules of gas and liquid which are further fractionated to produce other valuable products like gasoline, diesel and LPG. The leftover solid cracked material in the drum is then quenched, drained and drilled to produce the final product Coke that is high in carbon content. In a delayed coking unit, the coke drums work as a pair by alternating the coking and decoking process. As the decoking of an offline coke drum starts, the next coke drum is under operation which is filled up with the hot residuum through as switch valve. Alternating the coking between the drums make the coking a continuous process without halt. Therefore, it is typical to find Coker structures with two, four and eight coke drums operating continuously.

**Figure 1 - Delayed Coking Units - Courtesy of Structural Group, Inc.**

## COKER STRUCTURE

A Coker structure is a reinforced concrete construction in a refinery that supports multiple coke drums at an elevated platform called Table Top. The Table Top is a specialized concrete structure with octagonal penetration openings that are inscribed inside the circular base plate of the coke drum's skirt. Depending on the number drums, a table top has as many octagonal openings to support one coke drum per penetration. These octagonal penetrations are formed by a series of eight heavily reinforced concrete beams which are further supported on reinforced concrete columns down to the foundation. A coke drum is a tall cylindrical vessel made out of high chrome steel that typically measures 34m (110ft) in height and 8m (25ft) in diameter. The coke drum also includes a conical portion that extends up to 6m (20ft) at the bottom of the vessel through the octagonal penetration. The coke drums are attached to the concrete structure through a skirt plate mechanism which is combination of a vertical plate that is welded to the outer circumference of the vessel and a base plate that is anchored to the concrete with embedded steel rods/bolts.

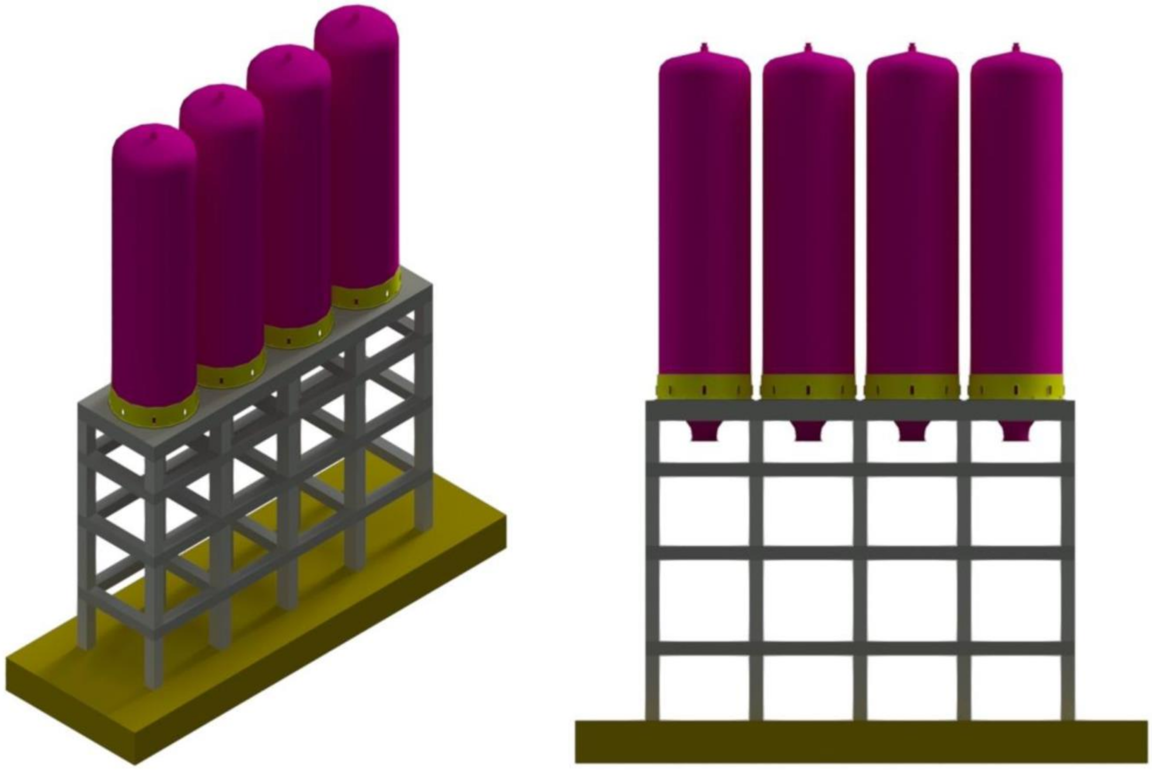

**Figure 2 – Isometric Layout and Elevation of a Coker Structure with 4 Coke Drums**

## STRESSES IN THE STRUCTURAL MEMBERS

The operational dead loads of the coke drums (up to $2.7 \times 10^6$kg) are typically the controlling loads for the design stresses in the structural members of a Coker structure. When the coke drums are operations, constant loading (coking) and unloading (decoking) of adjacent drums takes place because of the drums working in pairs. Because of this scenario, the octagonal penetration beams supporting the coke drums are subjected to differential gravitational forces causing flexural, shear and torsional stresses especially the center beams. The center beams are subjected to forces from loads due to adjacent drums. The coke drum that receive hot sludge during decoking produce high heat (510°C) environment through the conical portion at the bottom of the coke drums, while the next coke drum under decoking process produces considerably low thermal atmosphere. Hence, the intermediate beams supporting the adjacent drums are exposed highly fluctuating thermal stresses across the reinforced concrete section.

Additional loads that are considered in the design of a Coker structure are the lateral loads due to wind & seismic effects and dynamic process loads occurring during loading and unloading of coke drums. Since the coke drums are tall and massive, the wind and seismic effects create heavy lateral loads in the form of base shear on the anchor bolts and a moment that causes tension and compression force couple on the end beams supporting the base ring.

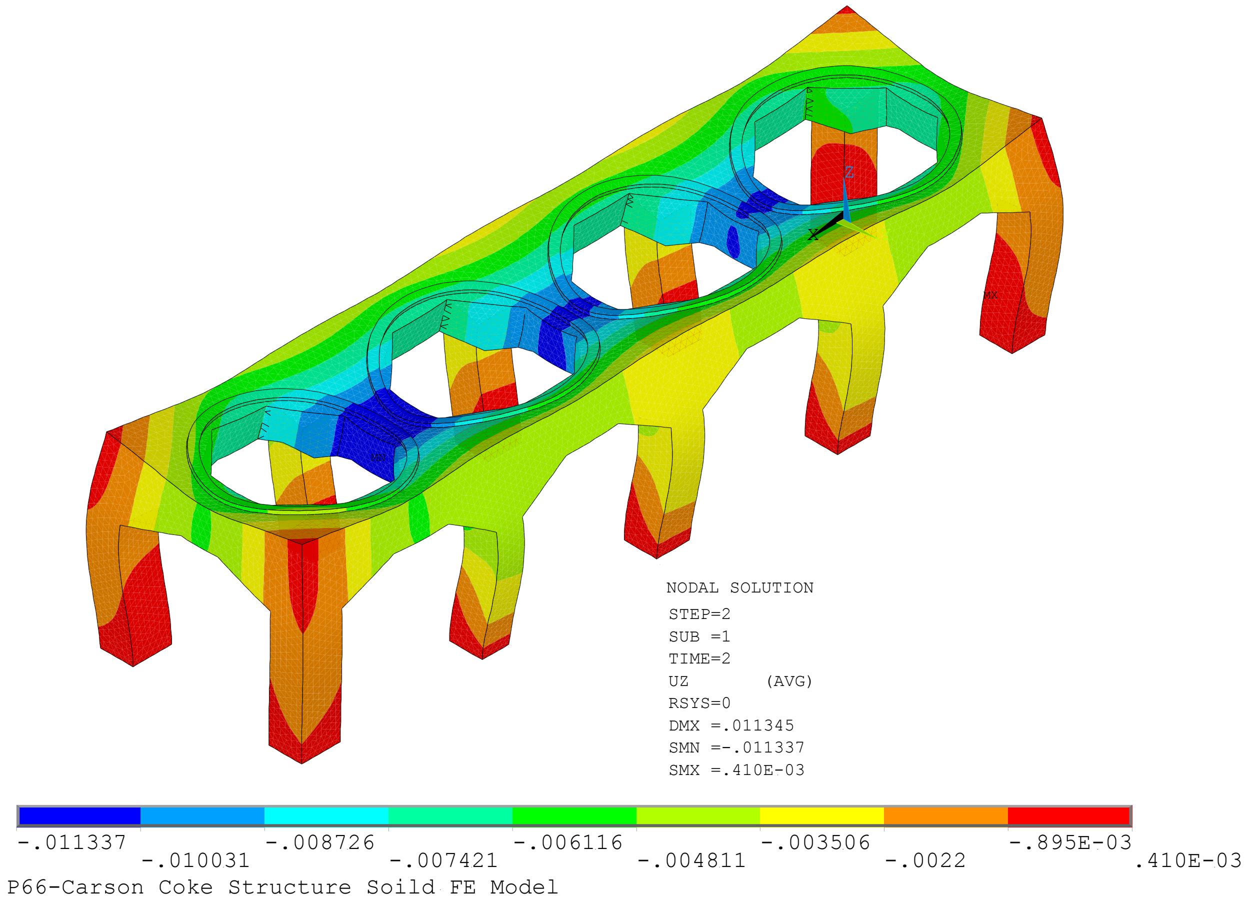


**Figure 3 – Stress Distribution in Structural Members of Coker Structure**

## CONDITION ASSESSMENT

Repair or restoration of a reinforced concrete structure involves intensive evaluation of the existing condition of the structural elements. The condition assessment generally involves measuring the limits of concrete delamination and the depths of deteriorations from the surface towards the embedded steel reinforcement (rebar) by using Ground Penetration Radar (GPR) and core drills. Any exposed rebar is examined for corrosion occurrence that may have caused loss of cross section. In order to determine the cause of deteriorations in the concrete and rebar, condition assessment involves Depth of Carbonation testing, Chloride Ion content testing and Non-Destructive testing such as Acoustic impact testing. If the design documentation regarding the material properties of the existing structure is not available, additional testing is performed to estimate the strength of concrete by performing Rebound Hammer testing on field and compressive strength testing in lab on the concrete core specimens extracted from the selected areas of the structure.

In a Coker structure, heavy concrete deteriorations are most commonly found on the surrounding interior faces of the octagon penetration beams which support the coke drums. The cause of this occurrence can be related to the obvious diminish in structural properties when concrete is exposed to heat surrounding the lower cone of the coke drum.

## DETERIORATIONS OBSERVED

Concrete exposed to fluctuations in temperatures lead to thermal cracking when tensile stresses exceed the tensile strength of concrete. The degree of thermal expansion in concrete mainly depends on the temperature range and age of the concrete. It has been found that, concrete in an octagonal penetration of a Coker structure surrounding the cone of the coke drum experience up to 177°C (350°F) of temperature during operating conditions. During decoking of coke drum this temperature decreases drastically causing a fluctuation in temperature of more than 93°C (200°F). The intermediate beams of the table top that support both operating and decoking drum at the same time can be subjected to a high temperature variation along its cross section. Though concrete performs exceptionally well under temperatures encountered in most applications, it can lose strength and stiffness when exposed to unusually high temperature gradients. The properties of concrete that get effected are compressive strength, flexural strength, and modulus of elasticity.

Concrete used in the design of a Coker structure, if not given special consideration for heat exposure can develop thermal cracking in concrete forming microcracks on the surface. These cracks if not treated can lead to chloride intrusion and atmospheric carbon dioxide ingression into the concrete cracks which further lead to chloride-induced and carbonation-induced corrosion of the embedded steel reinforcement respectively. These effects of corrosion ultimately lead to Spalling of concrete which is dislodgement of the concrete mass due to loss of bond with the steel reinforcement. Other deteriorations that are observed in a Coker structure are cross-sectional losses in anchor bolts due to corrosion, delaminated grout supporting the base plate of coke drum, loss of reinforced concrete sectional properties due to fire damage, and impact damages on the concrete surface due to mechanical equipment operating in the proximity.

Untreated delaminated grout lacks the bearing capacity to provide effective bearing surface for the Coker drum’s base plate. Under heavy loads, the grout crumbles causing tilting of drums towards failed grout. As the drums tilt, the anchor bolts on the tension side i.e., where the grout is intact are subjected to high tensile and shear load, which eventually lead to distortions and overstresses in anchor bolts.

## DESIGN ANALYSIS

Delayed coking in a refinery is batch-continuous process, where the flow from the furnace to the coke drum under operation is nonstop. Therefore, to maintain the continuity of the coking process, the repairs on the octagonal penetration beams are performed with coke drums in place. Engineers review the data obtained from the condition assessment of the structure in order determine the critical structural members which may jeopardize the structural integrity. A phased repair approach is then evaluated based on the observed sectional losses the structural members have endured and possible temporary redistribution of forces among the other structural members for the loads transferred from the coke drums. The deteriorated sections are design checked in accordance with applicable building codes in order to assess the reserve structural capacity available while performing the repairs. One of the major factor that determines phasing of repairs is if the drums are in operating condition (drum filled with coke & water) or decoking condition (drum emptied) during repairs. A coke drum under its operating condition weighs almost 10 times its empty weight. Therefore, Coker structure repairs with coke drums online require more number of repair phases, meaning area of deteriorated concrete that can be repaired at one time will be less when compared to repairs performed while the drums are offline thus increasing the construction time of repairs. Another factor to be considered in design of phasing is the turnaround time as the repair construction is required to be finished within the decoking time of the coke drum, so as to keep the coking process continuous.

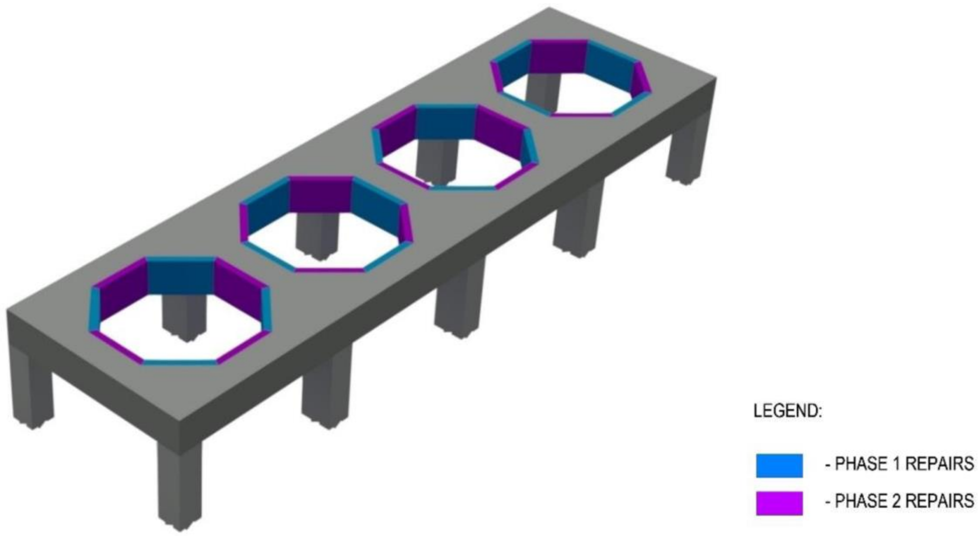


**Figure 4 – Phasing of Coker Structure Octagonal Penetration Beam Repairs**

Multiple iterations are run to check the existing structural capacity of the deteriorated members to determine the most optimal phasing considering the process times and turnaround times. The design check is performed by reducing the cross section of the reinforced concrete beam along with the number of reinforcing bars that are exposed in the deteriorated portion of the beam. In the octagonal penetration, if four alternate beams are considered to be repaired in one phase, then the load distribution from the coke drum is assumed to be acting on the remaining four beams causing the load intensity to be doubled on the deteriorated sections of the beams. If the beams under investigation were designed conservatively in their as-built condition, meaning the capacity of the beams being much higher than required, the reserve capacity of the reduced section of the beam should be enough to sustain the high intensity of loads. If the reserve capacity of the deteriorated beams is found to be not enough to take the high intensity loads, then the alternate options of shoring the beams or performing the repairs while drums are offline or more number of repair phases while drums are online are considered.

Repairs on concrete and rebar are necessitate performing surface preparation in accordance with International Concrete Repair Institute (ICRI) guidelines. The surface preparation of deteriorated concrete involves cleaning out, by abrasive blasting or high-pressure water jetting, the delaminated chunks of concrete to reach the sound concrete surface and chip up to two the rebar diameter behind the rebar. Based on the amount of deterioration and the chipping required for the repairs, the base plate of the drum’s skirt ring is undermined due to loss of bearing from the concrete. This ultimately leads to flexural stresses in the bearing plate. In order to avoid high flexural stresses in the bearing plate, the limits of repairs causing the undermining is eliminated.

Additional investigations that are necessary for the design of phasing are the skirt base plate and effect of grout delamination. Delaminated grout that causes the tilting of the coke drum generates high flexural stresses on the base plate in the unsupported region between the ends of the deteriorated grout. In order to overcome these additional flexural stresses in the plates, the delaminated grout is replaced with steel shims that are sized to the transfer the bearing stresses between the base plate and concrete. Since, the concentration of the stresses is much higher and is limited to the area of shim plate, the bearing strength of concrete is design checked. In cases, where drum tilting has occurred, the drums are repositioned by using hydraulic jacks that are placed between the skirt base plate and top of concrete to lift the drum. These jacks are operated by increasing pressure in low intervals, to make sure that the applied pressure is not greater than the tilted weight of the coke drum. The flexural stresses induced in the base plate due to loss of bearing also leads to warping of the vertical skirt plate.

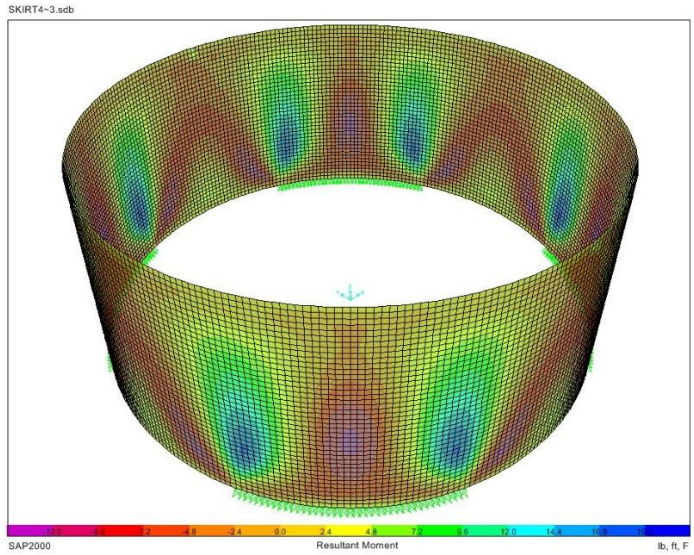


**Figure 5 – Flexural Stresses in Skirt Plate due to Unsupported Base Plate**

## REPAIR DESIGN

Restoration of a reinforced concrete structure is accomplished either as "repair in kind" or "repair to upgrade/strengthen". Repair in kind is implemented where the repairs are performed to bring the structure back to its as-built state in accordance the building codes established at the time of construction. Repair to Upgrade/Strengthen is implemented when repaired structure needs to pass the design requirements of the current building codes which sometimes is impractical in case of very old structure which were designed for less stringent design requirements.

When repair concrete is installed on top of existing reinforced concrete, the overall section behaves as a composite of new and old concrete. A successful repair of the reinforced concrete element is achieved by developing a design strength for horizontal shear transfer along the contact surface of the new repair concrete and existing concrete. The criteria for achieving this strength is to attain structural capacity of the overall section from the composite action of the two separate materials. According to ACI standard 318, the horizontal shear strength between two concrete surfaces can be achieved by intentionally roughening the existing concrete surface to a full amplitude of a 0.6cm (1/4in). If the required design shear transfer strength is not achieved by roughening, then shear transfer reinforcement that is developed into new and existing concrete is designed in accordance ACI guidelines.

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