Failure Analysis and design modification of stack spool bolts under mechanical/thermal loading using finite element model and experimental data: A case study

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Abstract:

Stacks are the most outstanding type of chimneys in gas refineries which located in the sulphur recovery unit. It is attached to incinerator in order to carry the H_2S combustion products (SO_2) away. Its structure consists of two casing. The outer one is reinforcement concrete wall while the inner one comprises 21 steel spools (3m and 6m length) and expansion joint at the bottom. Each two spools are connected together using 60 bolts (M12, alloy steel A325) and the final assembly hangs to stack, hanging from a steel platform. Four supporting platform devised in different levels to guide spools along the height. In the course of time, bolts run into creep and fail so top spools detached and fall. When top spools fail, lower spools lose their connections and their weights suppress guided supports and expansion joint at the bottom of stack structure damaging them. Several solutions were proposed ranging from using wire cables restraining spools to design extra supports for spools. Finally it was decided to change bolt materials to (alloy steel A193 B16) with higher thermal strength moreover designing sets of clamps to keep spools tight together. This is more cost effective in compare with mentioned solutions. Also this time stud bolt was used instead of previous regular hexagonal bolts to decrease stress concentration points. This new support modification does not create any limitations against natural air draft inside the stack between walls and flow gas line. In this article first root causes of stack bolts failure are analyzed and the proposed solutions are compared. Then the newly designed clamps technical characteristics are studied. Finally using a finite element model, thermal and mechanical load distributions on bolts are investigated before and after support design modification.

Keywords: steel chimney, finite element analysis, stress analysis.

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1- Introduction:

Sulphur recovery units is a very important section of sour natural gas refinery plant which design for conversion of hydrogen sulphide (H_2S) to element sulphur. Hydrogen solfied is a by product of processing natural gas .the most common conversion methods used is the Clus process ,approximately 90-95 percent of recovered sulphur is produced by the Clus process .

The waste gas stream from a modified-Claus sulphur recovery plant contains a number of sulphur compounds (COS,H_2S, SO_2)that cannot be release directly to the atmosphere. the usual method of destroying these compounds is incineration. Since the concentrations of the combustibles are too low for the waste gas stream alone to support, it is necessary to added fuel (gas) to the incinerator in order to sustain a flame and to attain the temperature necessary for the oxidation of the sulphur compounds. The main part of the incinerators is a Chimney which shall be hight enough for generating vacuums to induced air to incinerators combustion chamber. This design is based upon capacity of tail gas incinerators. A flue-gas stack is a type of chimney which its construction consists of a reinforced concrete (outer wall of the chimney) and separate flue duct inside inner wall that carries flue gases to the atmosphere. Thickness of outer wall is getting thinner along chimney to reduce weight. The inner part consist of vertical pipe, channel or similar structure through which combustion product gases called flue gases are exhausted to the outside air. Flue gases are produced. The bottom part of the stack wall has several openings for naturally induced air draft. In addition Access to the top of the stack for visual inspection of is provided by ladders and platform located inside the structure. Additional rectangular access door for cleaning and inspection is located at the ground level. These structures are so vulnerable because they are susceptible to various harmful mechanical – chemical thermal actions. They are exposed to harsh environments, both inside and outside. Flue gas, with its abrasive and corrosive characteristics, can damage the structural materials the chimney or refractories. Climatic conditions, ranging from high winds to extreme cold cause extreme stress on the structure itself. Combination of mechanical, chemical and thermal loads can cause various types of damage that can endanger the integrity of steel chimney structure. Also Chimneys are basically passive structures with few mechanical parts that require maintenance attention to keep them functional. So they often overlooked when plant maintenance and repair programs are developed. Because of this, it is easy to overlook them - but Failure of the chimney could be considered as a major accident, when chimney is fail all sulphur which is removed from plants natural gas (200 tons /day) shall be burned in flare stack until until maintenance jobs, for 20 days, maintenance job cost is about 100000$. This sulphur emission is so danger for environment. So design of large stacks causes considerable engineering challenges. Winds action which is in general critical to their design [1, 2]. Especially when fluctuating wind a velocity is at or near the chimney’s natural frequencies. Besides common failure happens for these types of structures, such as wind load, foundation settlement and earthquakes which lead to vibration forces, chimneys are subject to high chemical loads, vortex shedding and ring oscillation Owalling [3]. Also, special care has to be taken when designing a stack, since the operation condition can consider significant thermal loads of the structure. Complete combustion of hydrocarbons with air produces 3 hot gases, steam and carbon dioxide, in addition to nitrogen. Presence of small amounts of gases such as hydrogen sulphide in produced hydrocarbon gases leads to the production of small traces of gases such as sulphur dioxide. Moreover, extra heat reduces bolts strength and amplifies the effect of stress concentration in their structure. So they have a high potential to be damaged which have significantly influenced integrity of the inner spools. Generally Crack occurrence in materials is well documented and not unusual. Depending on structure type or material of purpose, different causes can initiate cracks in material structure. Corrosion [4], fatigue [5,6], stress concentrations due to inappropriate design [7,8], welding [9,10], or vibrations [11] are most common causes of crack initiation but it is usually a combination of several or all of these factors that initiate cracks in material structure [12,13]. This paper presents a practical example of a stack with bolt failure where it was not expected. Numerical analysis of failure occurrence was performed to investigate possible causes of bolt failure occurrence in inner part of south pars gas complex (phase 2&3) stacks and results were compared to experimental observations and manual specifications. Locations of extreme stress values for the bolts were identified numerically by finite element method. Identified locations coincided with the location of the cracks initiation and bolt failures. The aim of linear static stress analysis is to obtain stress field distribution and to identify stress concentration as the main cause of occurred failures the results of analysis identified causes of the failure initiation and allowed expression of the recommendation for root redesign of bolts and further maintenance procedures.

2: Stack

A 117m reinforced concrete chimney which located in Phase 2&3(south pars gas complex), serves a sulphur unit. This single flue stack is lined by 80 mm heavy refractory and high damping was expected. The stack is made in 21 flanged spools (6m-3m). All flanges are fitted with pre-stressed bolts. Basic dimensions of concrete stack, which is studied, are given in Table 1.

Table 1.Basic dimensions of concrete stack

HEIGHT (H)	117000 mm
INNER PART DIAMETER	2000 mm
1st GUIDE SUPPORT HEIGHT	8750 mm
2nd GUIDE SUPPORT HEIGHT	41000 mm
3rd GUIDE SUPPORT HEIGHT	75000 mm
REFRACTORY THICKNESS	80 mm
STRUCTURE WEIGHT	110000 kg
FLANGE DIAMETER	2200 mm
FLANGE WIGHT	250 kg

The combustion flue gases inside the flue gas stacks are much hotter than the ambient outside air and therefore less dense than the ambient air. That causes the bottom of the vertical column of hot flue gas to have a lower pressure than the pressure at the bottom of a Corresponding column of outside air. That higher pressure outside the chimney is the driving force that moves the required combustion air into the combustion zone and also moves the flue gas up and out of the chimney.

That movement or flow of combustion air and flue gas is called "natural draft", "natural ventilation", "chimney effect", or "stack effect". The taller the stack, the more draft is created. Flue gas is usually composed of carbon dioxide (CO_2) and water vapour as well as nitrogen and excess oxygen remaining from the intake combustion air. It also contains a small percentage of pollutants such as particulate matter, carbon monoxide, nitrogen oxides and sulphur oxides. The flue gas stacks are often quite tall, up to 400 metres (1300 feet) or more, so as to disperse the exhaust pollutants over a greater area and thereby reduce the concentration of the pollutants to the standard level. The flu gas data at the outlet of

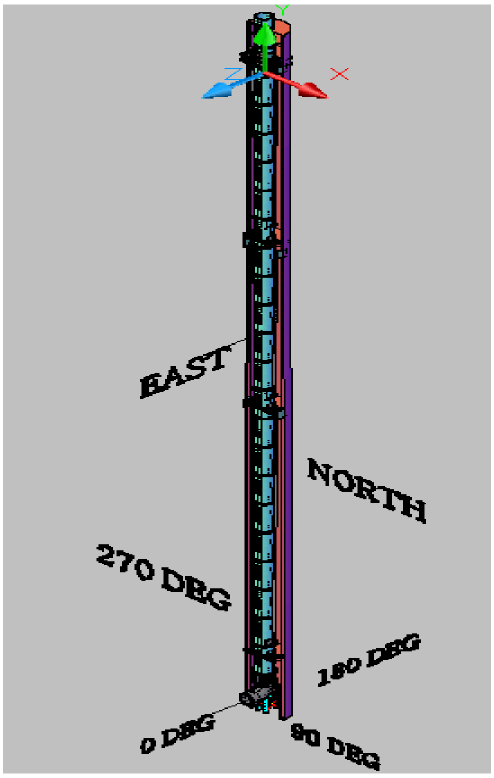


Figure 1 . Chimney 3D section view

Figure 2.sulfur recovery units stack

Incinerator is given on the following the design case, sensitive case and turn down case:

Table 2 .The flu gas data

	Design case	*Sensitive case*	*Turndown case*
Molflow (kmol/h)	2261.427	2178.954	594.053
Massflow (kg/h)	67418.1	66344.3	18777.0
Volume flow (Nm^3/h)	50687.6	48839.1	13315.1
Molweight (kg/kmol)	29.81	30.45	30.60
Temperature (°C)	540	540	540
Component (kmol)			
SO_2	13.325	11.479	3.711
CO_2	558.001	607.999	167.363
H_2	11.321	7.843	1.740
CO	8.722	8.027	2.355
O_2	45.229	43.579	11.881
N_2	1102.280	1019.440	279.220
H_2O	522.548	480.587	127.783

- The steel duct and breechings designed according to below requirements:

1- Free thermal expansions

2- Avoiding of vibrations

3- Avoiding of thermal bridges

4- Design temperature for inner steel duct is 650°C

- The available draft at the incinerator flue gas breeching is calculated operating pressure inside the incinerator chamber equal to -50 mm W.C
- Maximum flue gas velocity is limited to 15 m/s
- Material of the inner duct is alloy steel
- The wall temperature is maintained above the flue gas dew point for all operating case

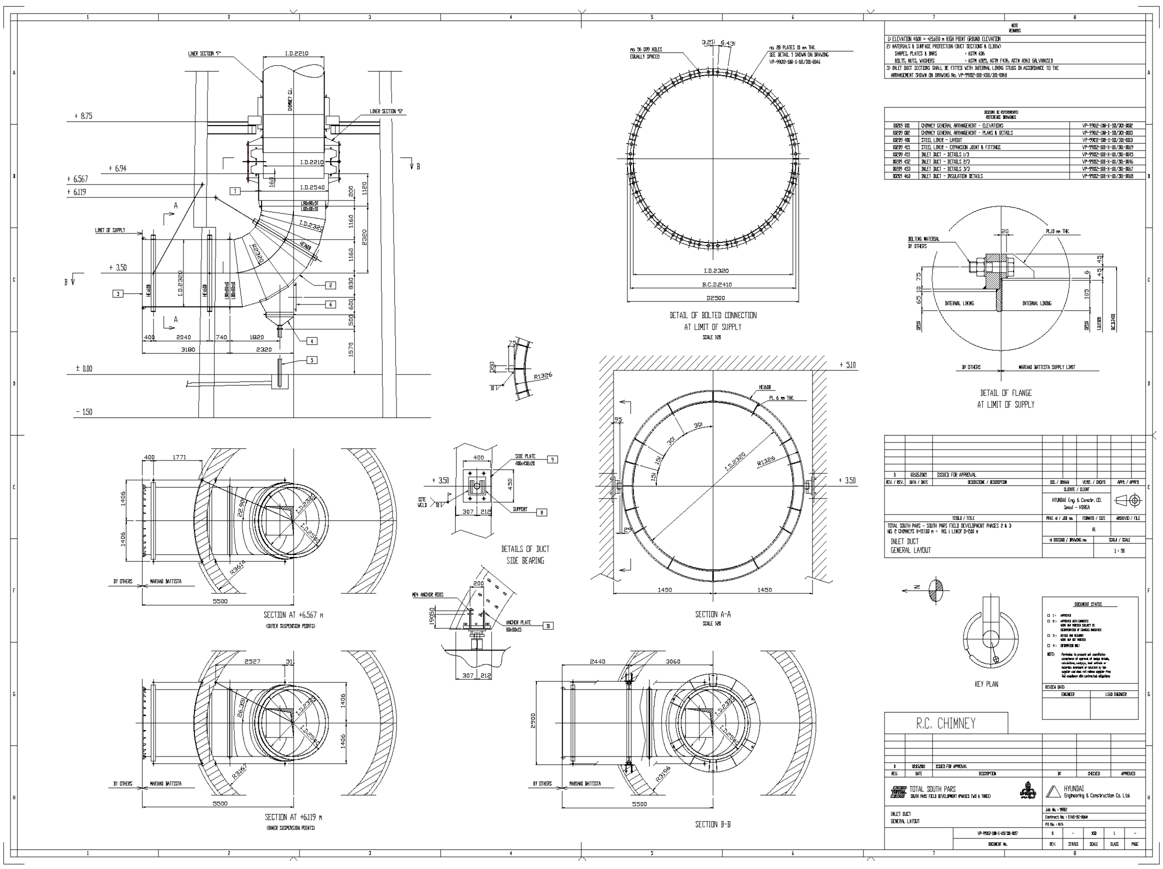


Figure 3.CHEMNEY DEATIL DRAWING

A few years after the stack was erected the bolts began to fail with replacement required Approximately every 3years. Failure happened on the 19 & 20 spools and when top spools fail, lower spools lose their connections and their weights suppress guided supports and expansion joint at the bottom of stack structure damaging them. An investigation was carried out and the main results are presented below.

3- Chimney Description:

The chimney is composed by an external reinforced concrete windshield and an internal steel liner Φ_i=2000mm hanging from a steel platform located at +108.75 m and guided at three different levels (+8.75m / +41m / +75m) by the mean of for tangential bumpers. The

Figure 4. Chimney hanger support s

Figure 5.spools flange with stud bolt

windshield consists of a reinforced concrete shell of variable diameter and thickness while the internal liner is composed by sections 6.0m long connected by bolted flange connections. The internal side of the steel liner is protected with insulation calcium silicate blocks (25mm thk.) and medium castable dense refractory (80 mm thk.) cast on situ prior to final lifting and assembling. The outer side of the steel liner is insulated with mineral wool mattress 30mm thk. Supported on pins. A general layout of the chimney arrangement and a detail of the inlet duct transitions curve and the expansion joint is hereby enclosed. Corresponding sketch is presented in Figure 6.

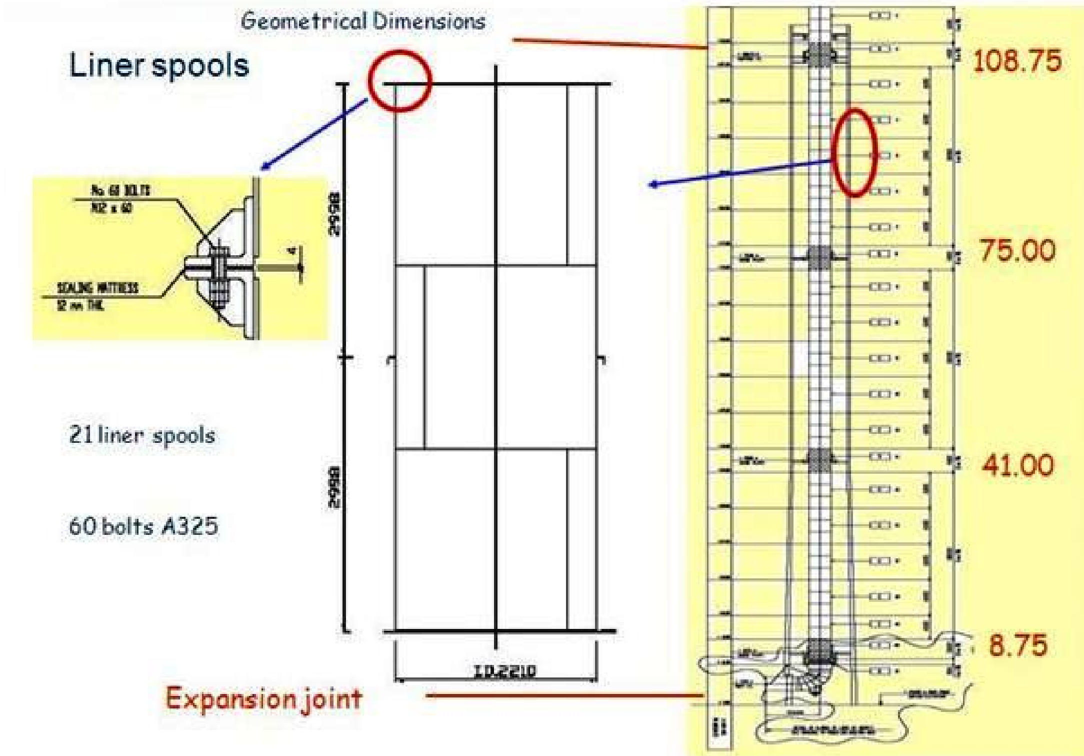


Figure 6. Stack Configuration sketch

Chemney wall component :

1- Insulating refractory cast able:

LICOFEST W202I

DENSITY: 1060 kg/m^3

2- Insulation board: CALCIUM SILICATE

DENSITY: 219.35 kg/m^3

3- Ss material

4- Insulated with mineral wool

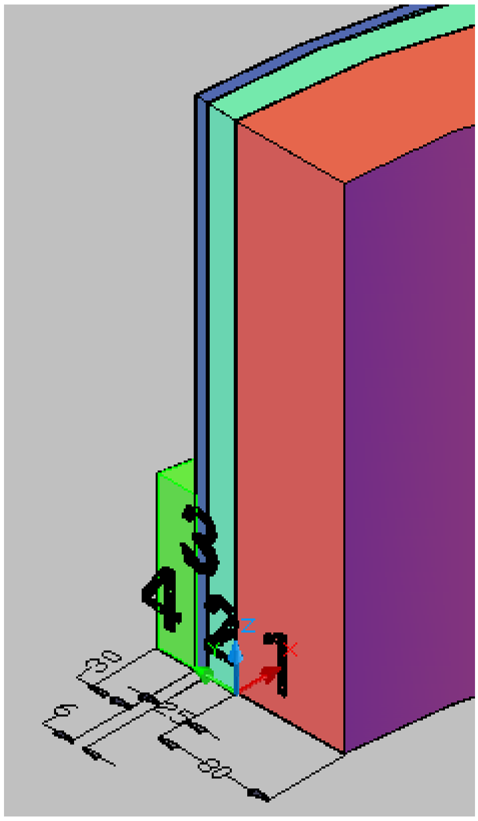


Figure 7.chemney section views

4- Observations

The failure of connecting bolts caused the liner to fall down of about 700mm finding a provisional support restrain on the 2 guide platforms located respectively at +41.00m and +75.00m. This failure is as a result of improper design of bolts, which should be reviewed. Another reason of the bolt failure is the exposure of bolts to the over design hot flue gas. Lack of proper flange joint sealing material (Ceramic Fiber) or insufficient amount of it will increase the exposure extents. High temperature extensively increases the rate of failure under static loads. The effect of the loading caused additional large deformations on the steel beams which have been subjected to high bending and torsion forces induced by the bumpers rigid connection. So we have distortion of guide platform H-beams at first, second and third elevations.

Due to the collapse of the liner the transition elbow has been subject to high vertical impact load which caused the failure of 2 tie rods connecting the curve to the concrete windshield.

In the same way the double-flexible expansion joint crashed together with the 6 vertical guide devices under the abnormal compression forces. So we have excessive compression of expansion joint and failure of its adjustable tie bolts

Figure 8. Damaged expansion joint

Figure 9. Stack fall down

Figure 10. Spool 20

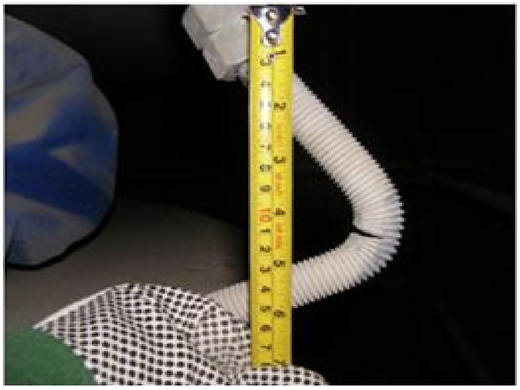


Figure 11. Expansion joint tie rod

Figure 12. chimney spool fall

Figure 13.chimney spool fall

The evidence of the failure of the connecting bolts located close to the hanging support of the liner has been detected as the main reason of the failure of the liner. Two main reasons for bolt failures were extreme heat and stress concentration on bolts.

Several methods were used to lift up and relocation of chimneys spools , 1.one by one spool lift up 2.all spool lift up which shown in next page picture.2nd method need to installs reinforcing plate on pick up spool

Figure 14. Spool relocation

Figure 15.

Bolts:

The function of bolts is to transfer load from one machine component to another .this load transmission may be to allow for transportation of power ,to keep components together and avoid leakage .there are a wide variety of threaded fasteners available including hex head. Figure --- is a drawing of a standard hexagon head bolt .point of stress concentrations are as the threaded(run out) and at the thread –root fillet in the plane of the nut when is present the material of the nut tends to take the entire load .

The bolts which used to connect chimney flanges are hexagonal head high strange structure bolt according ASTM A325, bolt size is 12 and this connection thigh with 60 bolts per flange. Failures occurs every 3 or 4 years at the flange NO 19 or 20 which higher load exist at this point. Bolt stress and load shown in table.3

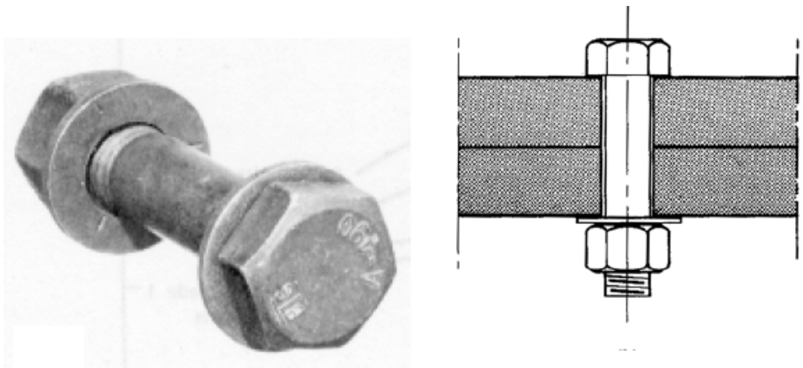


Figure 16.standard hexagonal head bolt

This stress concentration effect was severe on two points: 1- bolt head 2- at the beginning of the tread part where we have cross section area alterations. To overcome the limitations the material and type of bolts have been changed. Current bolt material (A-325) changed to higher strength material (A-193 B16) and machine bolt changed to stud bolt with double nut configuration. Using stud bolt instead of machine bolt reduce stress concentration points.

Besides, using double nut with pre load 100 (N.m) guaranty the appropriate strength for the structure.

Table 3, load for bolts on each stack level

Level NO	Force/bolt (*N*)	Stress σ (Mpa)	Level NO	Stress σ (Mpa)	Force/bolt (*N*)
Level 1	**372**	**4.72**	**Level 11**	**115.83**	**9093**
Level 2	**1244**	**12.44**	**Level 12**	**129.94**	**9965**
Level 3	**2116.3**	**26.90**	**Level 13**	**138.05**	**10837**
Level 4	**2988**	**38.06**	**Level 14**	**149.16**	**11709**
Level 5	**3860**	**49.10**	**Level 15**	**160.271**	**12581**
Level 6	**4732**	**60.20**	**Level 16**	**171.381**	**13453**
Level 7	**5604**	**71.40**	**Level 17**	**182.49**	**14325**
Level 8	**6476**	**82.50**	**Level 18**	**193.60**	**15197**
Level 9	**7348.8**	**93.61**	**Level 19**	**204.70**	**16069**
Level 10	**8220.9**	**104.73**	**Level 20**	**215.82**	**16941.8**

Type of broken and Location of bolt fail and broken was shown in picture 15 to 20

Figure 17 .Bolt head concentration points

Figure 18. Bolt concentration points

Figure 19.bolts crack

Figure 20.bolt analysis

Figure 21. Bolt dimensioning

Figure 22.Bolt and nut failure

Table 4.Result of tensile test bolts

Results of tensile tests on bolts.

Tests on A 325 Bolts				
Test Type	**Bolt Size**		**Tensile Strength (lbf)ᵃ**	**Notes**
ASTM F 606-02	7/8 in.×4.25 in.		69,000	failed in threads
ASTM F 606-02	7/8 in.×4.25 in.		68,000	failed in threads
ASTM F 606-02	7/8 in.×4.25 in.		69,300	failed in threads
		Test Rate (in./s)	**Tensile Strength (lbf)**	
load-elongation	7/8 in.×4.5 in.	0.00065	67,900	failed in threads
load-elongation	7/8 in.×4.0 in.	0.00065	68,300	failed in threads
load-elongation	7/8 in.×4.0 in.	2.0	68,800	failed in threads
load-elongation	7/8 in.×4.0 in.	2.0	68,200	failed in threads
Test on an A 490 Bolt				
Test	**Bolt Size**	**F_y (psi)**	**TS (psi)ᵇ**	**Notes**
A 370	1 in.×5 in.	153500	163500	16 % elongation in 2 in. ROA=59.5 %

After analysis and investigation about bolt failure location there for decide to change type of bolt and concentration point shall be removed then used to stud bolt with two nut on each side

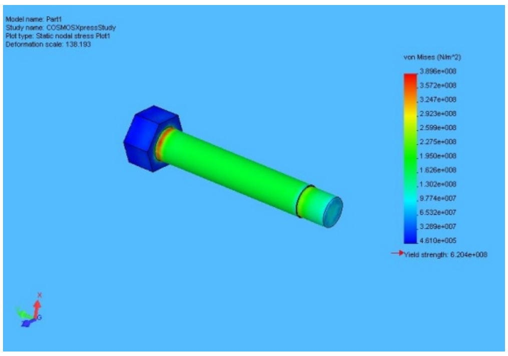


Figure 23

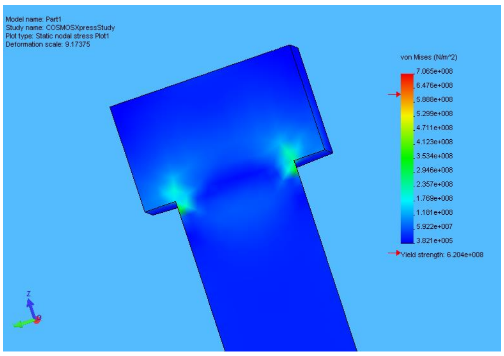


Figure 24

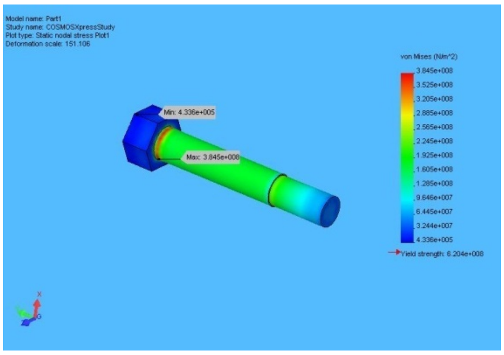


Figure 25

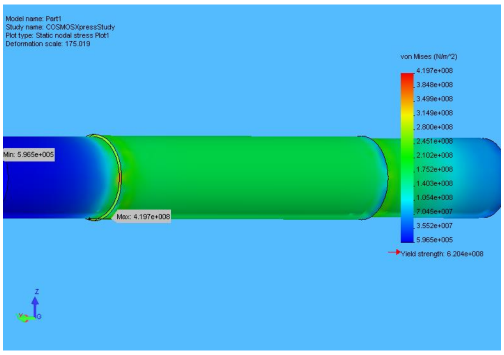


Figure 26

For added chimney stability and order to prevent lose and fall down chimney if the bolt was broken design high strength support for connect two flange together and according flange level and load select number of support which shall be used this support can be carry about 10 tons axial load then the chimney fall down is impossible.

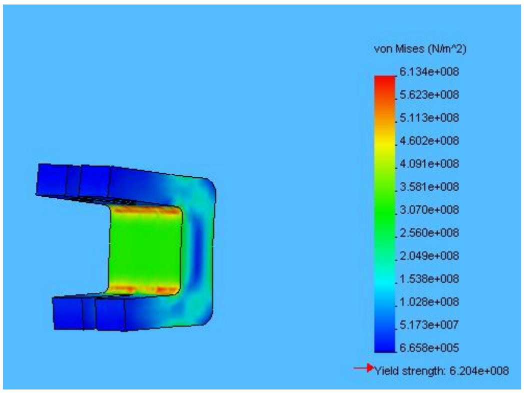


Figure 27.support analysis

Figure 28.support installation

Figure 29.one by one methods bolt renew

Figure 30.bolt renew by monkey man

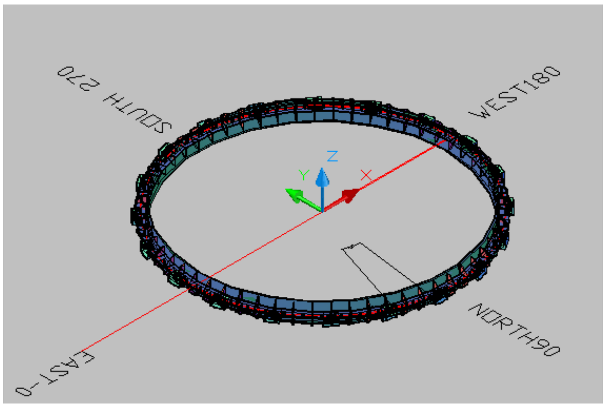
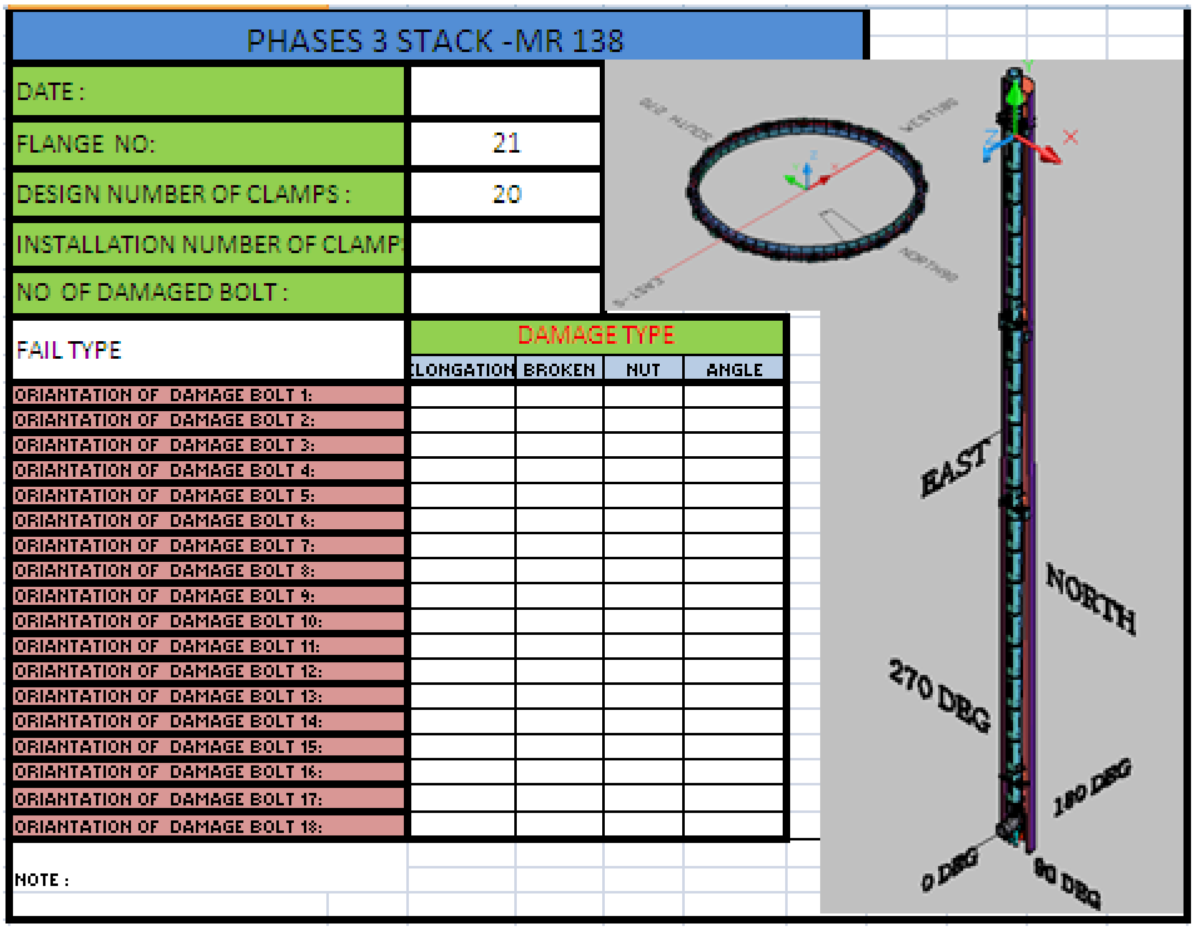


Figure 31

Figure 32



PHASES 3 STACK -MR 138				
DATE :				
FLANGE NO:	21			
DESIGN NUMBER OF CLAMPS :	20			
INSTALLATION NUMBER OF CLAMP:				
NO OF DAMAGED BOLT :				
FAIL TYPE	DAMAGE TYPE			
	ELONGATION	BROKEN	NUT	ANGLE
ORIANTATION OF DAMAGE BOLT 1:				
ORIANTATION OF DAMAGE BOLT 2:				
ORIANTATION OF DAMAGE BOLT 3:				
ORIANTATION OF DAMAGE BOLT 4:				
ORIANTATION OF DAMAGE BOLT 5:				
ORIANTATION OF DAMAGE BOLT 6:				
ORIANTATION OF DAMAGE BOLT 7:				
ORIANTATION OF DAMAGE BOLT 8:				
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ORIANTATION OF DAMAGE BOLT 16:				
ORIANTATION OF DAMAGE BOLT 17:				
ORIANTATION OF DAMAGE BOLT 18:				
NOTE :				

Figure 33.bolt and support inspection data sheet

Conclusion :

In this article we have investigated for all factors to fracture of stack bolts that connect inter spools of flue Exhaust gas inside stack. At first is explained previous stack maintenance in refinery and then several solutions is stated to overcome Bolt fragment. Finally with changing material of bolt to A193-B16 causes to reduce cost maintenance and more efficiency of Stable production and some conclusion are set forth as below:

- Stress concentration is reduce in new bolts
- Reinforcement of spool connection by installs metal clamps.
- Material changing is considered to increase mechanical and thermal strength.
- Reduce cost of maintenance and production in plant.

Material properties

Material **A 325 Type 1 (USA / ASTM)**

Group Structural and constructional steels

Subgroup ASTM A 325 / A 325M Quenched and tempered medium carbon steel bolts

Comment

Application

Yield Stress[MPa]			
Dimension	**Min**	**Max**	**Aprox**
Fastener; Quenched and tempered	660.00	-	-

Tensile Stress[MPa]			
Dimension	**Min**	**Max**	**Aprox**
Fastener; Quenched and tempered	830.00	-	-

Material properties

Material **A 193 B16 (USA / ASTM)**

Group Structural and constructional steels

Subgroup ASTM A 193 / A 193M Alloy steel and stainless steel bolting materials for high temperature service

Comment

Application

Yield Stress[MPa]			
Dimension	**Min**	**Max**	**Aprox**
Bar, fastener, wire; Heat treated; d < 65 mm	720.00	-	-
Bar, fastener, wire; Heat treated; 65 mm < d < 100 mm	655.00	-	-
Bar, fastener, wire; Heat treated; 100 mm < d < 180 mm	585.00	-	-

Tensile Stress[MPa]			
Dimension	**Min**	**Max**	**Aprox**
Bar, fastener, wire; Heat treated; d < 65 mm	860.00	-	-
Bar, fastener, wire; Heat treated; 65 mm < d < 100 mm	760.00	-	-
Bar, fastener, wire; Heat treated; 100 mm < d < 180 mm	690.00	-	-

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