CONSIDERATIONS FOR A SAFE IN SITU PWHT OF A CORRODED PROCESS TOWER

H.AYARI, M.M'HADHEB, DANIEL TRUONG AND K.T.TRUONG

Ultragen Ltd., Quebec, Canada

Department of Mechanical Engineering,

50, Rue de Lauzon, Boucherville, Québec, J4B 1E6

kt@ultragen.com

Abstract

A process tower in a petroleum refinery was subjected to severe corrosion under insulation (CUI) in two areas. It was discovered that the CUI was extended around the entire circumference of the tower and was confined to the vicinity of external rings. The remaining thickness in the shell in these areas ranged from 0.338" to 0.625" (0.625" being the original thickness). The weld overlay procedures were used to restore the vessel thickness to its original design values. Following the client's inspection department, the vessel after its repair by welding shall be heat treated in situ to 1200°F. At this temperature, the mechanical strength of carbon steel material is tremendously reduced and it is dangerous to perform the PWHT on the entire circumference of the tower in vertical position. In the present work, a parametric finite element model was developed to analyze the vessel subjected to the PWHT. The model was used to determine the safe temperature profile while respecting the imposed PWHT temperature, and to evaluate the maximum circumferential length to be covered by heat patches. This provides a sound basis to be considered in the PWHT process to ascertain that the entire operation is safe and respects the code requirements

***Keywords**: Corrosion under insulation, Finite element, Heat treatment, Heat transfer, Pressure vessel.*

1. PROBLEM

Damage from corrosion mechanisms often leads to failure in refinery equipment, creates safety hazards which interrupt refinery operations. The corrosion under insulation (CUI) phenomenon occurs in insulated vessels when the vessel shell is in continuous contact with insulation that has become wet and thus establishes the mechanism for oxidation and loss of material. During a routine external inspection, the removal of the insulation around the shell of a process vessel revealed that the CUI was extended around its entire circumference (Fig.3). The remaining thickness in affected areas of the shell ranged from 0.338" to 0.625" (being the original thickness). The tower was assessed for potential risk of collapse and an external weld overlay technique was used as a permanent repair method that restored the corroded areas to original thickness.

Usually, the weld metal zone is stronger than the parent metal but has less ductility. The heat affected zone is the region where most cracking defects are likely to occur because the grain structure becomes coarse just beyond the fusion line and the ductility is lowest at this point. The effect of the welding heat on the parent metal depends on the temperature reached, the time temperature is held, and the rate of cooling after welding. Thus the welding operation generate a harder heat affected zone, tensile residual stress and cold cracking susceptibility in the weld zone as well as in the base metal [1, 2, 3, 4, 5, 6, 7, 8].

That is why the proper heat treatment after welding (Post Weld Heat Treatment) is one that renews the material as near as possible to its original state [9, 10]. The process of post weld heat treatment (PWHT) consists of uniform heating of a vessel or part of a vessel to a suitable temperature for the material below the critical range of the base metal, followed by uniform cooling. This process is used to release the locked-up stresses in a structure or weld in order to ''stress–relieve'' it. Due to the great ductility of steel at high temperatures, usually above 1200 ºF, heating the material to such a temperature permits the stresses caused by deformation or straining of the metal to be released. Thus postweld heat treatment provides more ductility in the weld metal and a lowering of hardness in the heat-affected zone (HAZ). It also improves the resistance to corrosion and caustic embrittlement [11, 12, 13, 14, 15].

Heat treatment procedures require careful planning and will depend on a number of factors: temperatures required and time control for material; thickness of material and heating band width sizes; and contour, or shape, and heating facilities. If a vessel is to be fully postweld heat treated as shown in figures 1 and 2, the furnace should be checked to make sure that the heat will be applied uniformly and without flame impingement on the vessel. Vessels with thin walls or large diameters should be protected against deformation by internal bracing. The vessel should be evenly blocked in the furnace to prevent deformation at the blocks and sagging during the postweld heat treatment operation (Fig.2). During this operation, both the increase and decrease in temperature must be gradual in order to allow uniform temperatures throughout [9, 10].

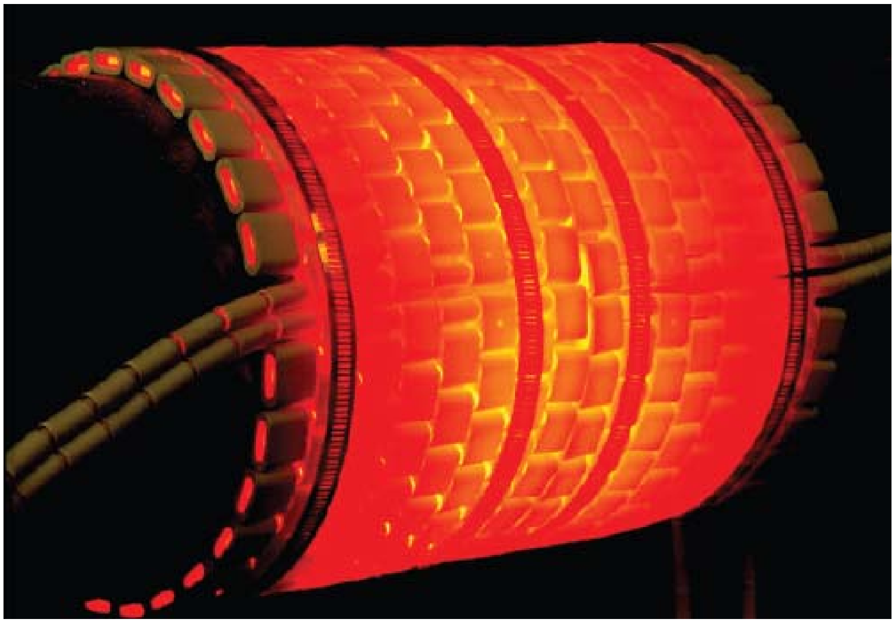

Figure 1: Example of PWHT applied on vessel circumference

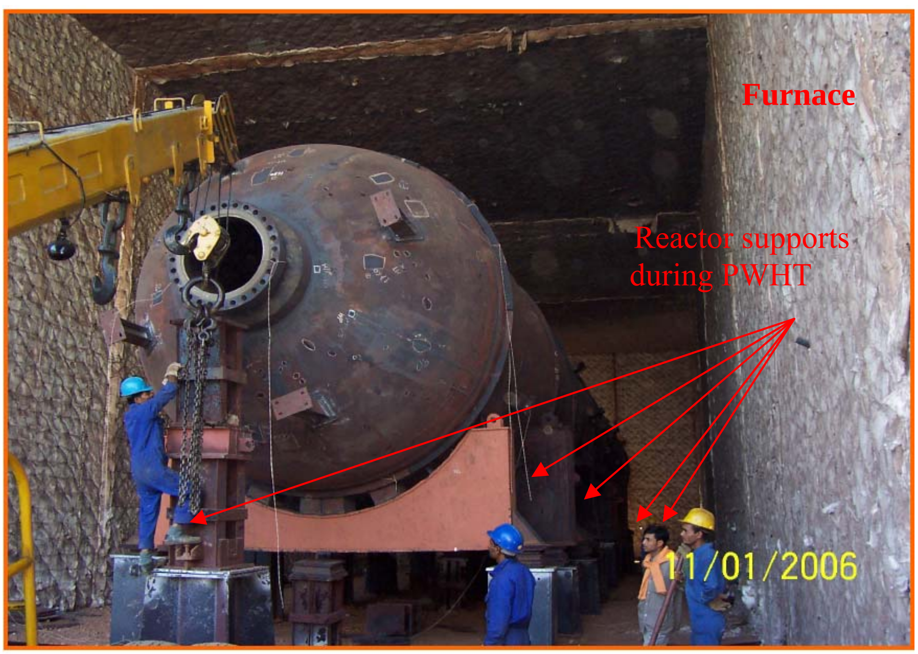

Figure 2: Preparation for PWHT performed on fully supported horizontal vessel

The ASME code Section VIII Div.1 [9] requires postweld heat treatment of a pressure vessel for certain design and service (Par. UW-40). Postweld heat treatment requirements (according to the material, thicknesses, service, etc) include the following:

- All carbon steel weld joints must be postweld heat treated if their thickness exceeds 1.25 in or exceeds 1.5 in if the material has been preheated to a minimum temperature of 200 ºF during welding (code Par. UCS -56).
- Vessels containing lethal substances must be postweld heat treated (Code Par.UW.2).
- Unfired steam boilers with a design pressure exceeding 50 psi must be postweld heat treated (Code Par.UW.2).
- Some vessels of integrally clad or applied corrosion –resistance lining material must be postweld heat treated when the base plate is required to be postweld heat treated (Code Par.UCL.34)

It is important that the PWHT conditions be determined based upon the desired objectives. For a successful PWHT, it must be based upon engineering assessment and optimization of many parameters to meet the desired objectives. According to the WRC 452 [10] the main parameters are:

- Temperature gradient through material thickness that is defined by two important parameters: the heating rate and band size.
- Induced stresses and distortion during PWHT (compression and bending during heating, creep relaxation during holding, global stress recovery upon cooling)
- Gradient control band: an important factor to control the axial temperature gradient and to minimize heat losses.
- Axial temperature gradient: the control is important to limit thermal stress and to protect the vessel outside of the band
- Other considerations:
  - Equipment support during heating;
  - Buckling and Distortion;
  - Internal Liquids;
  - Thermal Expansion.

Details of the corroded vessel in consideration are as follows. Figure 3-a and 3-b show the distribution and extent of corroded areas along the developed surface area of the tower. In our case it is impractical to heat treat the whole vessel that is why a local PWHT should be performed in situ.

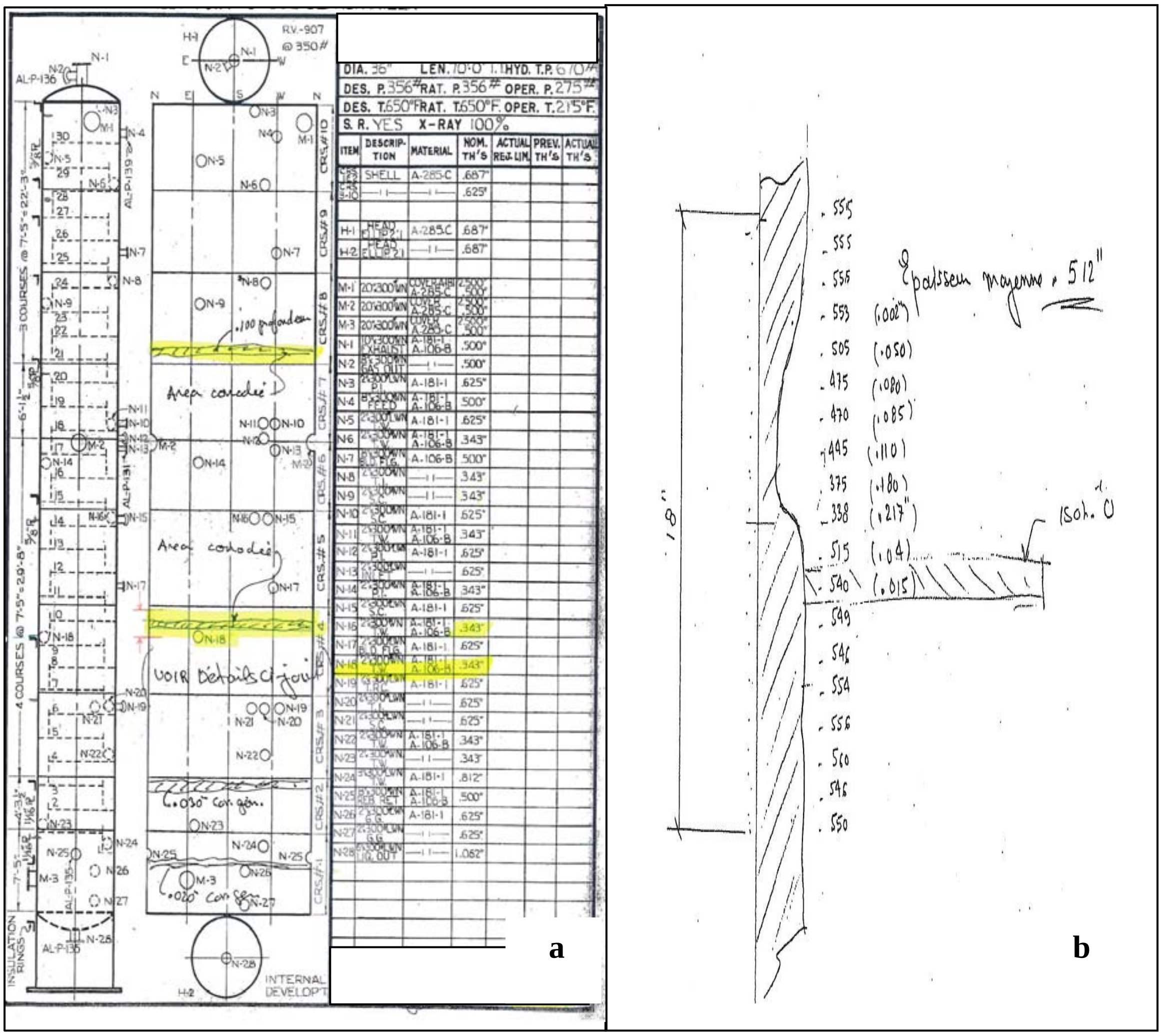

Figure 3: Corroded area (a), Inspection sketch (b)

According to the ASME code Section VIII Div.1 [9], our pressure vessel required a localized PWHT to reduce the induced residual stresses when is subjected to local welding. Therefore, it is very important to analyse if the in situ PWHT can be performed in safe conditions; to determine the optimal temperature profile and the maximum heated circumferential band width in order to reduce the unit downtime. Two distinct studies were accomplished as engineering activities before the PWHT. The first part of this study is to determine the mechanical loads due to weight and wind during PWHT. The second part is to assess its impact on the equipment mechanical integrity to ascertain that the entire operation is safe and respects the code requirements.

2. GUIDELINE FOR A LOCAL PWHT ANALYSIS

The tower was assessed for potential risk of collapse and an external weld overlay technique was used as a permanent repair method that restored the corroded areas to original thickness. If the tower is subjected to local repairs, a localized PWHT is mandatory to reduce the induced residual stresses. The inspection group has determined that a vertical dimension for the applied heat patches is of 26 inches to cover the required area with a damaged height of 18 in (26 in =18in+2*6*0.625in) and a maximum temperature for the Post Weld Heat Treatment of 1200°F. A parametric finite element model was developed to analyze the heat treatment after welding, determine the optimal temperature profile and the maximum circumferential length covered by heat patches.

The vessel in consideration was analyzed using COSMOS/M 2.9 finite element software. All the cylindrical sections of the tower and the skirt support were included in the numerical model (76Ft). A parametric finite element model was created to investigate different circumferential dimensions for the PWHT area. Four different circumferential lengths were considered: 1/8 the circumference, 1/6 the circumference, 1/4 the circumference (about 29'') and 1/3 the circumference. The model was created using 4-node thin "Shell4" elements with membrane and bending capabilities.

2.1. Geometrical parameters for the FE model/analysis (see Figure 1 and 6):

- Outside diameter: 37 in
- Corroded wall thickness: 0.5 in (original wall thickness of 0.625in minus original CA of 0.125in)
- Material of construction: SA-285 C
- Tower height: 76 Ft (the skirt length is included)
- PWHT

2.2. Thermal and mechanical material properties

The thermal and mechanical properties (ASME, Section II, Part D, 2007 [16]) were defined as a function of temperature:

- Thermal conductivity TC [Btu/sec in °F]

Table 1: Thermal conductivity

T(°F)	250	350	400	450	…	700	1100	1150	1200
TC	7.62e-4	7.31e-4	7.15e-4	7.01e-4	…	6.16e-4	4.84e-4	.000468	.000451

- Convection & radiation coefficient for vertical surface [Btu/in^2 sec °F]

Table 2: Convection & radiation coefficient

T(°F)	130	180	230	280	…	1030	1080	1200
h	3.55e-6	4.13e-6	4.67e-6	5.2e-6	…	19.02e-6	20.49e-6	26.35 e-6

- Thermal expansion coefficient [in/in/°F]

Table 3: Thermal expansion

T(°F)	70	100	200	400	…	800	900	1000	1200
α	4.6e-6	6.5e-6	6.7e-6	7.1e-6	…	7.8e-6	7.96e-6	8.1e-6	8.3 e-6

- Modulus of elasticity [psi]

Table 4: Modulus of elasticity

T(°F)	70	200	300	400	…	700	800	900	1200
E	29.3e6	28.6e6	28.1e6	27.5e6	…	25.3e6	24e6	22.3e6	15.4e6

2.3. The allowables

Thermal stress: According to the classification of ASME Code Sect. VIII Div.2 [17], the stresses due to temperature gradient are considers secondary stresses. The calculated stress intensity should be compared with the allowable stress S that is equal to two (2) times the average tabulated yield strength of the material for the highest and lowest temperature.

$$S = S_{yc} + S_{yh} \qquad (1)$$

- **Syc**: Material Yield Strength at ambient temperature = 30,000psi
- **Sy**h: Material Yield Strength at PWHT temperature = 15,000 psi (extrapolated value). Since the ASME, Section II, Part D [16] only covers Yield values up to 1000°F, for higher temperatures the required value was extrapolated.

In this case the allowable stress (S) is equal to 45,000 psi.

Thermal strain: The thermal strains for the PWHT operation were compared with 0.2% strain "margin" as recommended in WRC 452 [10]. The strain range of 0.1 to 0.2% in/in is the proportional limit of steel and is also a characteristic parameter in the curve of stress vs. strain of metal according to the Hooke's law.

Static stress: The evaluation criteria for the tower and support skirt were established using ASME, Section VIII, Division 1, 2007, UG-23(b) [9] for allowable longitudinal

compressive stress in a cylinder. This stress is a function of the diameter, thickness, and temperature (length does not enter into this particular calculation).
The allowable compressive stress *B* at design conditions was determined following the steps in UG-23(b):

- A = 0.125 / (R / t)
- Using the value *A* in Fig. CS-2 from ASME, Section II-D or Table CS-2 [16], for a particular design temperature, the allowable compressive stress *B* is determined.

For the present work, the allowable longitudinal compressive stress (B) at design temperature of 650°F is 10,818.93 psi.

Buckling: The buckling analysis of the tower is done following the method of Bifurcation Analysis. This analysis is based on the load resistance factor design (LRFD). According to ASME Section VIII Div.2 Part 5, 2007 edition [17], the allowable safety factor LRFD is calculated using the formula:

$$\mathbf{LRFD=2/Beta} \tag{2}$$

where Beta = 338 / (389 + D/t).

Hence, the minimum safety factor against buckling (**LRFD**) must be of 2.64. The margin of safety in the design takes also into account for manufacturing imperfections.

Maximum deflection (DEF_a): Based on practical rules, the vessel deflection during PWHT is limited to 6 in per 100Ft. For the tower in consideration, the maximum permissible deflection DEF_a is 4.56 in per 76 Ft.

2.4. Boundary conditions

The bottom nodes of the skirt base are restrained in all direction. The weight (80,085 lbs) is applied as a distributed load on the upper edge of the tower. The shear forces at different levels of the tower due to wind are distributed over the half circumference. To reflect the reality, it was considered that the applied loads follow a sinusoidal distribution on the contours. The decomposition of wind shear forces (*Fs*) is based on the approach described in the following paragraph.

In fact, a point load *Fs* applied over a cylindrical contour (Fig. 4) can be decomposed as elementary forces (F_{s_i}) having a sinusoidal shape:

Thus the point force Fs (shear force) is equal to:

$$Fs = \sum_{1}^{N} F_{s_i} \tag{3}$$

where N is the number of nodes along half of the circumference.

and F_{s_i} is the nodal shear force that is equal to:

$$F_{s_i} = F_r \sin\theta_i \quad \text{and} \quad \frac{F_{s_i}}{F_{s_{i+1}}} = \frac{\sin\theta_i}{\sin\theta_{i+1}} \tag{4}$$

Fr is a uniform radial force equal to:

$$F_r = \frac{Fs}{\sum_{1}^{N} sin\theta_i} \tag{5}$$

The angle θ_i defining the node position is equal to:

$$\theta_i = (i-1)(\frac{\pi}{N-1}) \; ; 1 \le i \le N ; \quad 0 \le \theta_i \le \pi \tag{6}$$

Figure 4 illustrates the distribution of the point load Fs in nodal forces F_{s_i} of sinusoidal shape.

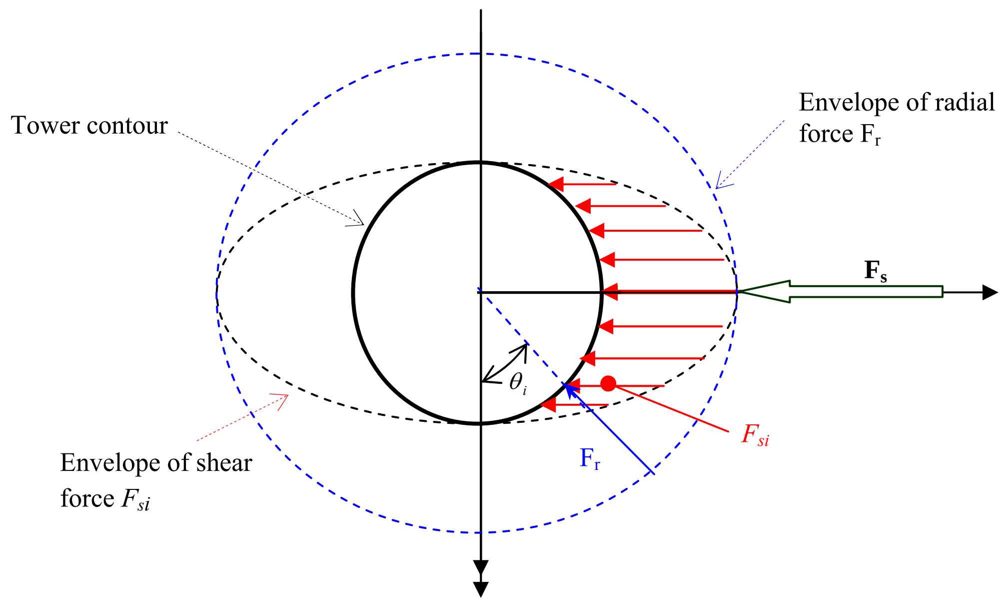

Figure 4: Sinusoidal distribution of the point load F_s

Bending moments (*M*), due to the wind, are transformed into elementary forces distributed over the contours of the tower. A sinusoidal shape distribution was also adopted and the sum of these elementary forces should be equal to zero.

If we consider a half of circumference (symmetry) the moment can be decomposed as below. Let *M* be a moment on the tower contour and F_i a nodal force at θ_i (Fig.5). This force will induce an elementary moment M_i.

$$M_i = F_i * X_i \tag{7}$$

$$\text{with } X_i = R\, sin\theta_i \text{ and } M_i = F_i * R\, sin\theta_i \tag{8}$$

The moment on a half vessel contour is equal to:

$$\frac{M}{2} = \sum_{1}^{N} M_i \tag{9}$$

where N is the number of nodes along half of the circumference.

$$\frac{M}{2} = RF_1 \sin\theta_1 + 2RF_2 \sin\theta_2 + ... + 2RF_{n-1} \sin\theta_{n-1} + RF_n \sin\theta_n \tag{10}$$

where

- n is the number of nodes along the ¼ of circumference,
- $\sin\theta_1 = 0$; $\sin\theta_n = 1$ (θ_1=0°; θ_n=90°) and $n = \frac{N+1}{2}$

$$\frac{F_{n-1}}{Fn} = \frac{\sin\theta_{n-1}}{\sin\theta_n}; \frac{F_{n-2}}{F_{n-1}} = \frac{\sin\theta_{n-2}}{\sin\theta_{n-1}};........; \frac{F_3}{F_4} = \frac{\sin\theta_3}{\sin\theta_4}; \frac{F_2}{F_3} = \frac{\sin\theta_2}{\sin\theta_3} \tag{11}$$

The angle θ_i, defining the node position is equal to:

$$\theta_i = (i-1)(\frac{\pi}{2(n-1)}) \ ;0 \le \theta_i \le \frac{\pi}{2} ;1 \le i \le n \tag{12}$$

By a simple substitution we can deduct the nodal force F_i applied on half of vessel contour (Fig.5).

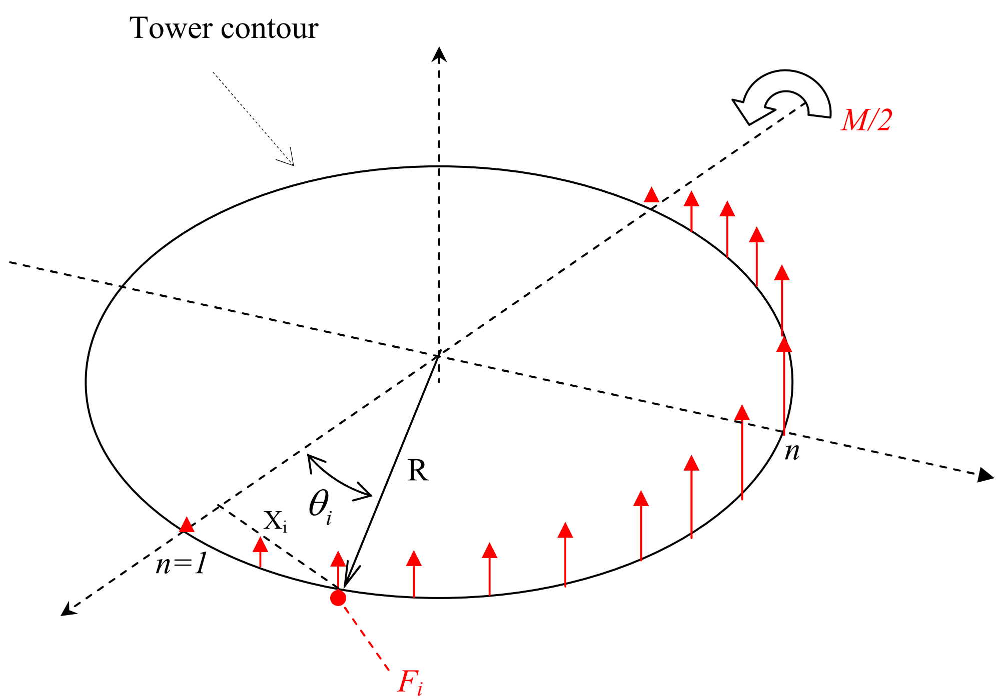

Figure 5: Force distribution to create an overturning moment

2.5 Circumferential heated band width and optimal applied temperature profile

The vessel is erected on the site and a local PWHT could not be performed on the entire circumferential length without causing an imminent collapse of vessel. It is then important to optimize the heated circumferential length while assuring the mechanical integrity of vessel. A steady state heat transfer analysis is then required to determine the temperature profile of the vessel around the PWHT area limited by the circumferential dimension of the PWHT patch. A temperature of 1200°F was used, as a maximum temperature, for the area exposed to PWHT. The optimal temperature profile and the heated area are determined by an iterative simulation as showed in the flowchart below (Fig.6).

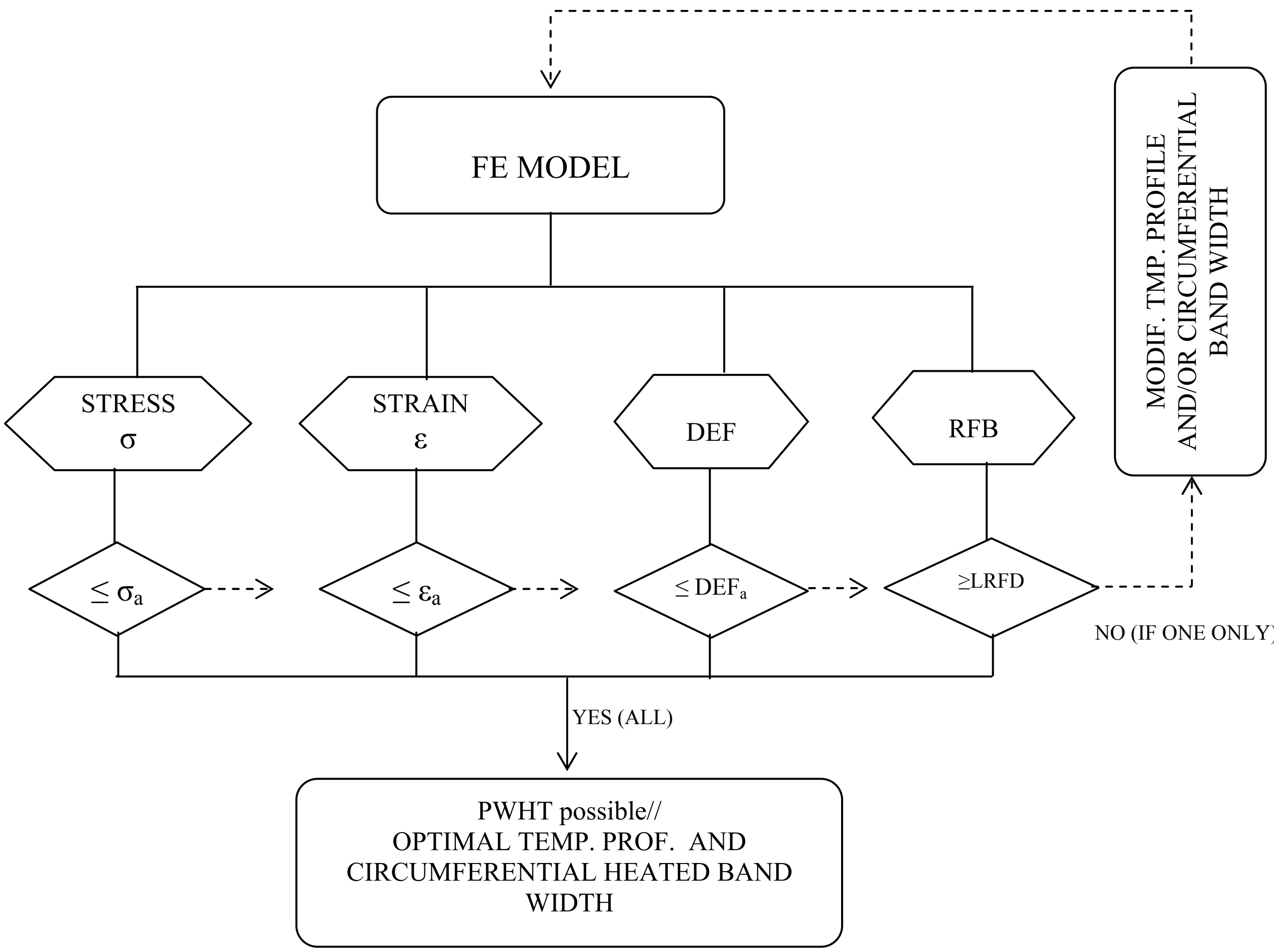

Figure 6: Flowchart of iterative calculation

RFB: risk factor of buckling obtained by FE; DEF: Deflection at the vessel top obtained by FE.

σ_a combined allowable stress; ε_a: allowable strain

The ASME code Section VIII Div.1 (UW para. 40) and WRC Bulletin 452 [9, 10] require a gradual degradation in temperature around the treated area in order to minimize the effect of a sudden drop. It is therefore recommended to have a controlled temperature profile around the portion subject to PWHT.

To obtain an acceptable level of thermal stress, deflection, strain and without any risk of buckling, the temperature beyond the treated area should be kept to 650±50 °F (Fig.7). At this temperature (650±50°F) the mechanical strength of metal can be considered same as at ambient temperature (the tower is built before 1999). Also, this condition ensures a relatively uniform expansion all around the circumference (not localized) that minimises the deflection of the tower. In addition, analysis of the different circumferential lengths of PWHT area has showed that the FE model with ¼ of vessel perimeter (29") respects the code limitation and represents a maximum length to reduce the downtime of the affected vessel.

For the tower in consideration, the green area subjected to a controlled temperature ranging from 600 °F to 700 °F must have the following dimensions: the cylinder perimeter and along the vertical axis covered by the affected height plus 2 times of 24". Figure 7 shows the optimal temperature profile and dimensions of the heated area determined by iterative calculation according to the flowchart shown by Fig.6.

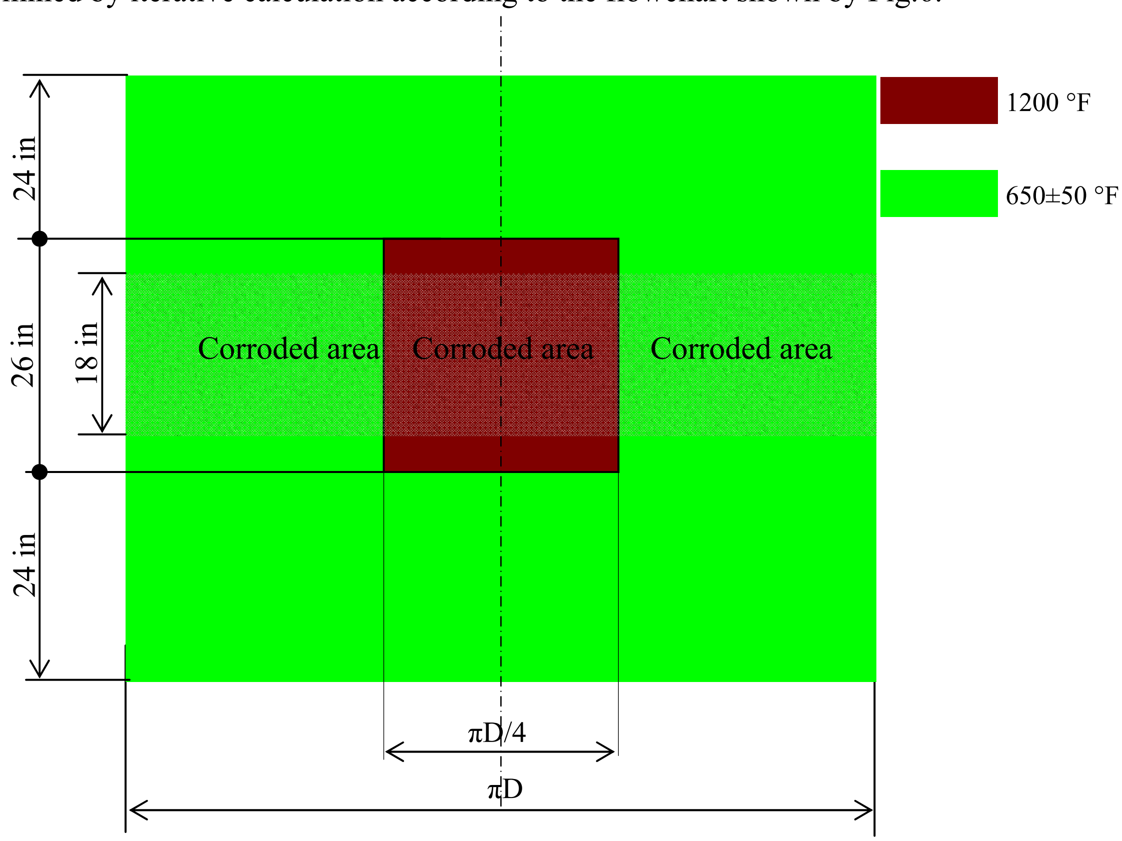

Figure 7: Zone of controlled temperature and circumferential heated band width

3. RESULTS OF THE ANALYSIS

3.1 WIND LOADS

According to the refinery's inspection, the extent and severity of the thickness loss are immediately recognized as a safety hazard. As a first security measure, a preliminary analysis was conducted in according to the ASME Section VIII Div.1 [9] to determine the minimum code thickness; and as per the National Building Code of Canada 2005 [18] for the loads that are supported by the tower due to the weight and wind. The heat treatment operation will be performed in situ during the shutdown. Hence, the mechanical loads present during the PWHT are identified as below:

- **Dead loads:** The total weight of the tower in new condition (to be in the safe side), platforms, ladders, attached piping, fire proofing, insulation and internals.

- **Wind loads:** The wind pressure during PWHT is considered equivalent to the hydrostatic test case. This is typically as low as one – third of the design load, since it can be assumed that the vessel will not be PWHT during a hurricane or severe storm.

The tower was then recalculated using the original design conditions. Data used for calculations are summarized in Table 5.

Table 5: Original design conditions

Design Temperature	650^{O}F
Internal design pressure	350 psig
External design pressure	Non specified
MDMT	-20^{O}F
Hydrostatic pressure	670 psig
Corrosion allowance (shell/top head/bottom head)	0.125''/0.217''/0.207''
Radiographic Test	100% X-Ray
Efficience joint	95%
Material	SA-285 C

The main parameters used to calculate the wind loads, as defined by the NBC2005 [18] and customer specifications are summarized in Table 6.

Table 6: Wind parameters

Wind parameters	
Importance factor I_w	1.0
Shape factor $C_{f\ (Cylinder)}$	0.7
Shape factor $C_{f\ (platforms)}$	1
Wind pressure q (kPa)	0.4
Site class	A

The output results show that the minimum thickness required (0.625'') exceeds the remaining thickness measured by the inspection group (0.338''). The total weight of the tower including water and materials in new condition, platforms, ladders, attached piping, fire proofing, insulation and internals is 80,085 lbs. The platforms and ladders have also been modeled in order to properly reflect the effect of wind. Applying the NBC2005 [18] and the Customer Specifications to determine wind loads, we find that the bending moment computed at the bottom of the skirt is 130,672 lbs-Ft. In addition, the wind velocity should not exceed 50 Km/h during PWHT (for Montréal East) to ensure a 33% of design wind loads applied at the tower.

Figure 8 and Table 7 present the loads for the critical loading condition corresponding to the hydrostatic test case of a new tower.

Table 7: Wind Loads

Location	Elevation d_j (*Ft*)	Total wind shear (lbf) per component (Fs_j)	Bending moment (lbf-Ft) per component (*Mj*)
Bottom Top Head	75.134	29.30	13.18
Bottom course #10	67.717	459.320	5436.432
Bottom course #9	60.300	408.370	-1227.44
Bottom course #8	52.884	230.620	860.344
Bottom course #7	46.759	183.890	574.578
Bottom course #6	39.342	393.870	6514.642
Bottom course #5	31.925	203.170	760.5092
Bottom course #4	24.509	196.960	730.395
Bottom course #3	17.092	313.310	-1824.07
Bottom course #2	12.801	278.830	6421.514
Bottom course #1	5.384	197.370	687.9633
Bottom Support Skirt	0.0	281.280	-3798.16
Fs_T *and* M_T *at bottom Support Skirt*		$Fs_T = \sum Fs_j = 3176$	$M_T = \sum Mj + \sum Fs_j * d_j = 130672$

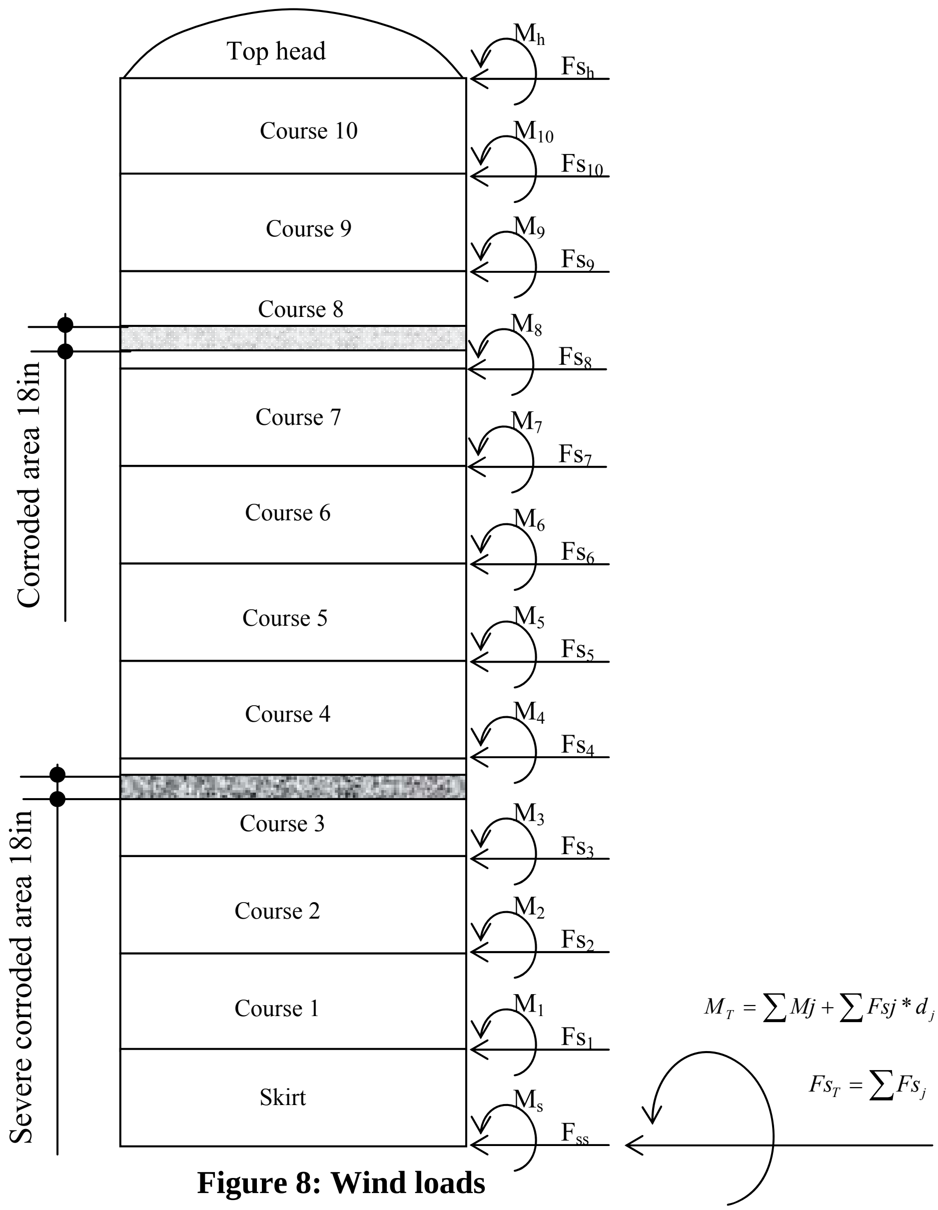

Figure 8: Wind loads

3.2. STRESSES EVALUATION

The stress evaluation is conducted in accordance with the rules of ASME Boiler and Pressure Vessel Code, Section VIII, Division 2, Part 5 [17]. In this finite element study three types of analysis were performed to assess the mechanical integrity of the vessel during the PWHT: thermal analysis, static analysis, combined analysis (thermal + static) and buckling.

3.2.1. Temperature profile

The optimal temperature profile and heated area are determined by an iterative simulation as showed in the flowchart (Fig.6).

The calculated temperature profile resulting from the heat transfer analysis around the exposed area to PWHT is shown in Fig.9.

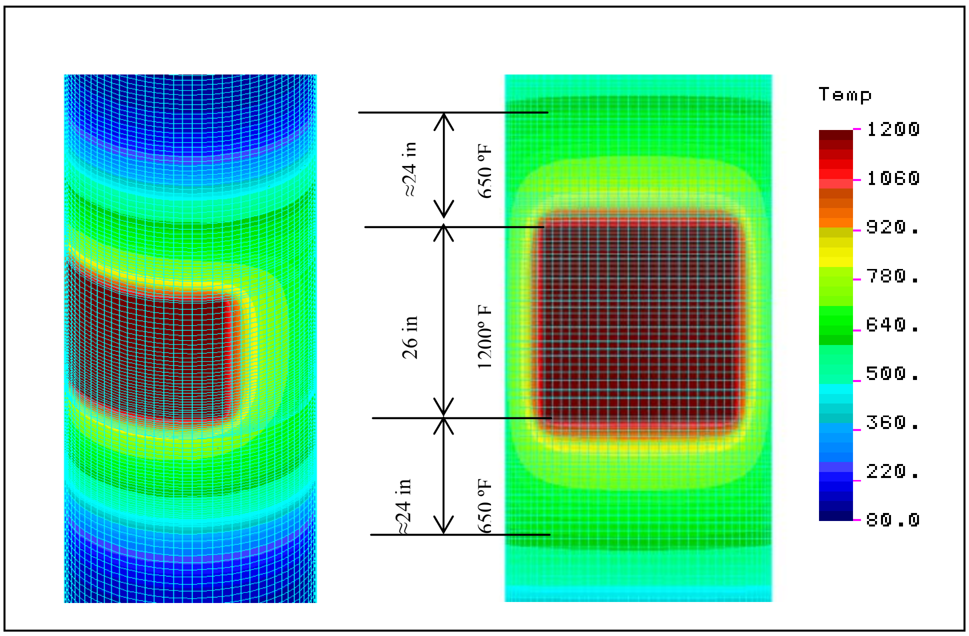

Figure 9: Proposed temperature profile

Based on the determined nodal temperatures, the stress intensities, equivalent strain, deflection, and risk of buckling were reported in this paper.

3.2.2 Stress results

Thermal stress intensities: The thermal stress intensities resulting from the temperature distribution (Fig. 9) are shown in Figure 10.

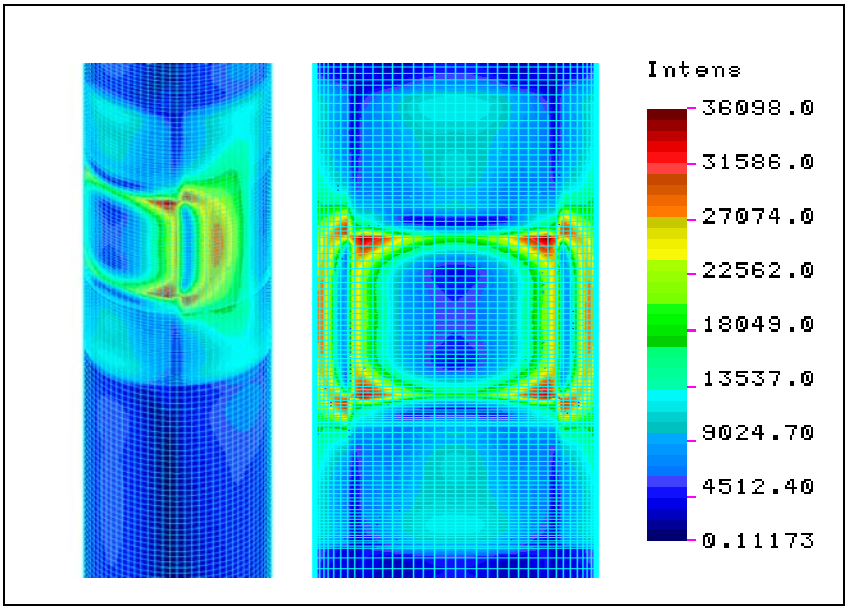

Figure 10: Thermal stress intensity due to PWHT.

Using the thermal boundary conditions described, the maximum stress intensity is of 36,100 psi. Thus the calculated stress by FE is inferior to the allowable stress permitted by the ASME code (45,000 psi).

Static stress intensities: This section presents stress intensity related to mechanical loads applied on the tower (weight and wind). The stress intensity obtained by the FE due to the weight and wind is shown in Figure 11.

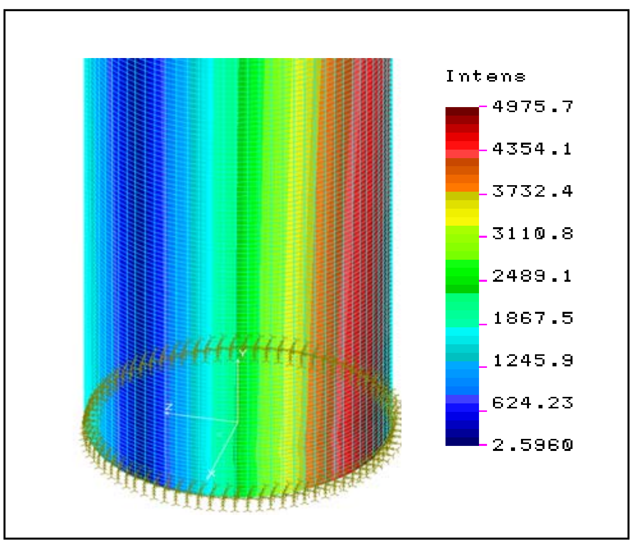

Figure 11: Stress Intensity due to weight and wind.

The maximum stress intensity, as expected, is located at the bottom of the support skirt which is remote from the PWHT area. The stress intensities values were calculated using the mechanical properties as a function of the temperature profile determined during the thermal study of the finite element model. The calculated stress intensity at the bottom of the skirt are small compared with the allowable stress (4976 psi versus 10818 psi).

Combined stress intensities: In this section we present the results of the combined loading case. Three critical cases of wind application can arise during the PWHT:

- Case 1: Wind acts on the back of the heat-treated area,
- Case 2: Wind acts on the front of the heat-treated area,
- Case 3: Wind acts on the side of the heat-treated area.

The stress intensity obtained by the finite element model, due to the combination of mechanical and thermal loading is shown in Figure 12. The maximum stress is obtained for case 1 (most critical case). The maximum stress is equal to 38,553 psi. This stress remains less than the allowable stress (45,000psi).

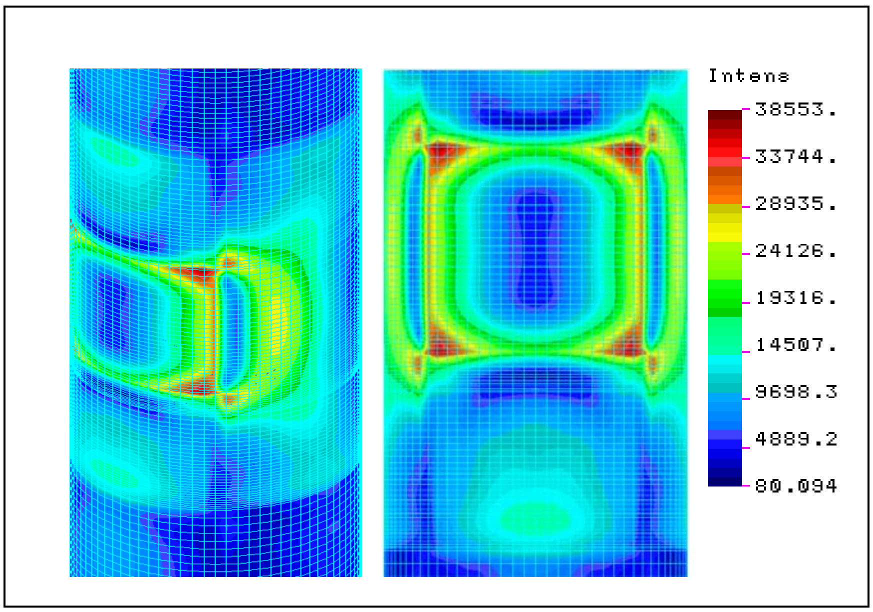

Figure 12: Stress Intensity for combined loading (case 1)

3.2.3 Strain results

Figure 13 shows the equivalent strain in the case of combined loads. The largest deformation is observed in the case where the wind acts on the side to the area subjected to PWHT.

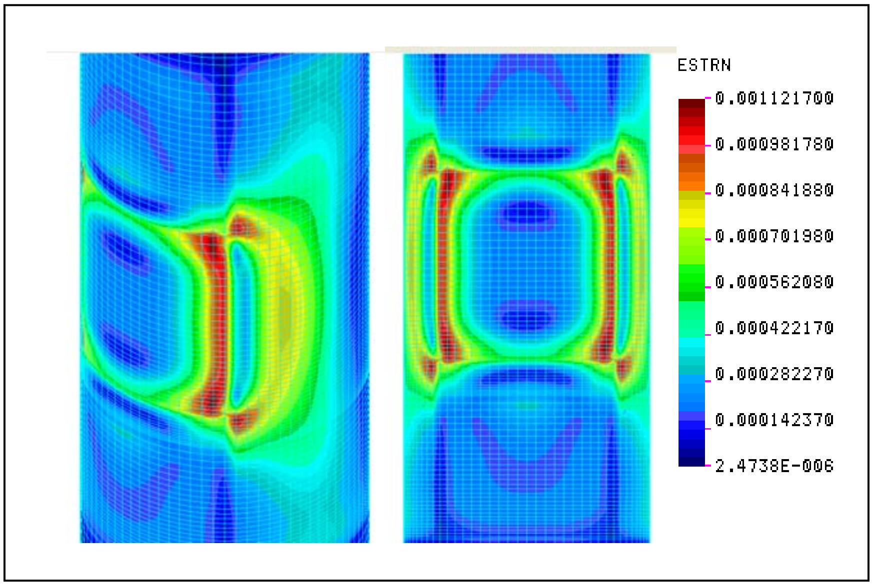

Figure 13: Equivalent strain

The maximum strain calculated for the combined load case is equal to 0.122%. This deformation is also acceptable and inferior to 0.2%, assuring that the tower stress state stays within the elastic limit.

3.2.4 Deflection verification

Figure 14 shows the deflection of the tower due to combined loads. The maximum deflection is 4.31" and it is observed at the top of the tower. This displacement is considered acceptable because the maximum displacement allowed is 4.56" per 76Ft.

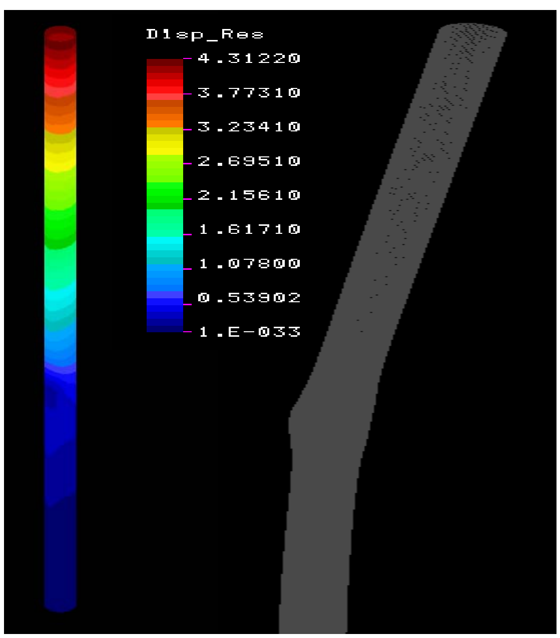

Figure 14: Deformed shape (combined loading)

3.2.5 Risk Factor of Buckling (RFB)

To be more conservative, in the buckling analysis we considered the PWHT area (which has a very low modulus of elasticity @ 1200 ° F) as an opening in the finite element model. Based on the calculated heat transfer profile, the heat treated zone is characterized by a centered high temperature that attenuates gradually to 650°F. Thus the approximate dimensions of opening are 40"*36" (Fig.15-a).

The results show that the calculated Risk Factor of Buckling is equal to 5.45, which is greater than 2.64 (theoretical permissible value for buckling). This demonstrates that the tower is capable of sustaining the current load without any risk of buckling during the PWHT. Figure 15 shows the deformed shape and the risk factor of buckling of the tower with an opening.

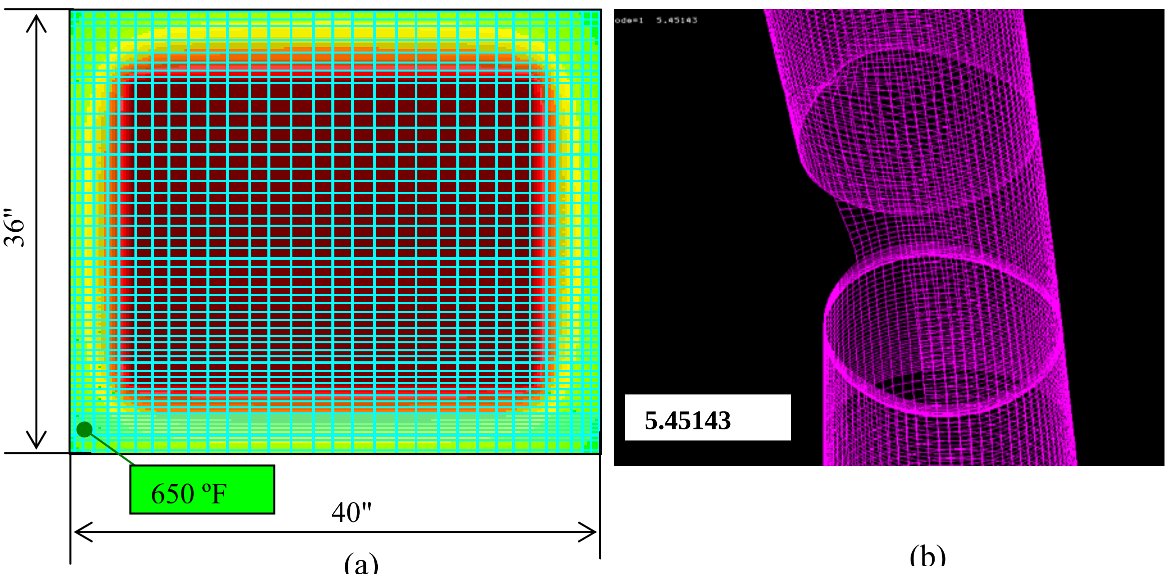

Figure 15: (a) Opening dimensions, (b) deformed shape

4. CONCLUSIONS

This paper presents a numerical approach using the finite element technique to analyze a tower subject to PWHT in the field. The analysis is accomplished in accordance with ASME Code Section VIII, Division 1 & 2 [9, 17], the National Building Code of Canada 2005 [18] and the recommendations of WRC Bulletin 452 [10]. The minimum required thicknesses as well as the induced loads due to the weight and wind were obtained in accordance with the NBC2005 design parameters.

According to the procedures of ASME Code Section VIII Div.2, the calculated stress intensities were found to be of acceptable values, and thus do not permanently deform the vessel shell and/or cause buckling. As stated in this paper, the combined stresses were compared with S with the hot yield value extrapolated from the ASME

Code Section II, Part D [16] since at the PWHT temperature the hot allowable stress for the SA-285 Gr.C material is not available.

The verification of thermal strains induced in the vessel around the PWHT area becomes necessary and recommended by WRC Bulletin 452 [10]. Thermal strains are calculated based on "displacement fields" which in this case are temperature related. The calculated strains for the PWHT operation were compared with 0.2% strain "margin". The calculated thermal strain around the PWHT area is of 0.122% (max.).

The results from the thermal analysis demonstrate that the temperature around the treated area should be maintained from 600°F (min) to 700°F (max) to not induce excessive stresses and deflection. The detailed dimensions of the area that must have a controlled temperature are shown by Fig.9. For the tower in consideration, the analysis showed that the PWHT patch length should be limited to 1/4 of vessel perimeter (about 29"). In addition, during PWHT the wind velocity should not exceed 50 Km/h (Montréal East) to ensure a 33% of design wind load applied on the tower.

This approach can be generalized and applied for different size of corroded vessel subjected to in situ PWHT. In the presence of a local discontinuity (for instance, a nozzle located inside or near the PWHT area), a more detailed FE model should be developed to take this into consideration.

Nomenclature

PWHT: post weld heat treatment
CA: corrosion allowance, in
I_w*: importance factor*
C_f*: shape factor*
q: wind pressure , kPa
CUI: corrosion under insulation
MDMT: Minimum Design Metal Temperature, °F
d_j*: elevation from skirt bottom, Ft*
E: modulus of elasticity, psi
A: thermal expansion coefficient, in/in/°F
h: convection & radiation coefficient for vertical surface, Btu/in^2 *sec°F*
TC: thermal conductivity, Btu/sec in°F
Syc: material Yield Strength at ambient temperature, psi
Syh: material Yield Strength at PWHT temperature, psi
S: allowable thermal stress, psi
B: allowable longitudinal compressive stress, psi
LRFD: load resistance factor design
DEF_a*: maximum deflection, in*
RFB: Risk Factor of Buckling obtained by FE
DEF: deflection at the vessel top obtained by FE, in.
D: skirt outside diameter, in
t: thickness, in
σ_a*: combined allowable stress, psi*
ε_a*: equivalent allowable strain, in/in*

σ: calculated stress by FE, psi
ε: calculated strain by FE, psi
Fs_j: shear force at course j (j=1,….10), lb
Mj: bending moment at course j (j=1,….10), lb-Ft
Fss: shear force at skirt, lb
Fsh: shear force at head, lb
Ms: bending moment at skirt, lb-Ft
Mh: bending moment at head, lb-Ft
F_{ST}: total shear force
M_T: total bending moment, lb-Ft
Fs: shear force, lb
Fs_i: nodal shear force, lb
Fr: radial nodal force, lb
M: bending moment, lb-in
F_i: elementary bending force, lb
M_i: elementary bending moment, lb-in
F_i: nodal bending force, lb
Xi: lever arm, in
N: number of nodes on half circumference
n: number of nodes on 1/4 circumference
θ: angle(°)
R: skirt radius, in

Acknowledgements

The authors gratefully acknowledge the technical and financial support provided by the Ultragen Group Ltd/ Engineering Consultant.

References

[1] Q. Xue, D. Benson M.A. Meyers, V.F. Nesterenko E.A. Olevsky, Constitutive response of welded HSLA 100 steel, Materials Science and Engineering A354: 166_ 179 (2003)

[2] J. E. RAMIREZ, S. MISHAEL, AND R. SHOCKLEY ,Properties and Sulfide Stress Cracking Resistance of Coarse-Grained Heat-Affected Zones in V-Micro alloyed X60 Steel Pipe, Welding Research, welding journal : (2005)

[3] Hisaki OKABAYASI and Ryochi KUME, Effects of Pre-and Post- Heating on weld cracking of 9Cr.-1 Mo-Nb-V Steel, Transaction of the Japan Welding Society, Vol.19, No.2: (1988).

[4] R. Scott Funderburk, Key Concepts in Welding Engineering- fundamentals of Preheat, Welding Innovation Vol. XIV, No. 2,: (1997)

[5] Tadashi Kasuya, Nobutaka Yurioka, Makoto Okumura ,Methods for predicting maximum hardness of Heat Affected Zone and selecting necessary Preheat temperature for Steel Welding, Nippon Steel Technical Report No.65,: (1995)

[6] Teng, Tso-Liang, Chang, Peng-Hsiang, , A study of residual stresses in multi-pass girth-butt welded pipes, International Journal of Pressure Vessels and Piping 74: 59–70 (1997).

[7] Lee, S., Kim, B.C., Kwon, D., Correlation of microstructure and fracture properties in weld heat-affected zones of thermomechanically controlled processed steels, Metallurgical Transactions A,:(1992).

[8] Eigenmann, B., Schulze, V., Vo¨hringer, O., Surface residual stress relaxation in steels by thermal or mechanical treatment, In Proceedings of the Fourth International Conference on Residual Stresses, Society of Experimental Mechanics, Bethel, Connecticut, Baltimore, MD,:598–607(1994).

[9] ASME, 2007, ASME Boiler & Pressure Vessel Code, Section VIII, Division 1.

[10] WRC Bulletin 452: Recommended Practices for Local Heating of Welds in Pressure Vessels by J. W. McEnerney and Pingsha Dong - June 2000. Library of Congress Card Catalog: 85-647116 (64 pages).

[11] G. Thomas, V. Ramachandra, R. Gamesman and R. Vasudevan, Effect of pre- and post-weld heat treatments on the mechanical properties of electron beam welded Ti-6Al-4V alloy, Journal of material science, volume 28 :4892-4895(1993).

[12] A.G. Olabi and M.S.J. Hashmi**,** The effect of post-weld heat-treatment on mechanical-properties and residual-stresses mapping in welded structural steel, Journal of material Processing Technology, Volume 55, issue 2,: 117-122 (1995).

[13] M.S.J. Hashmi and A.G. Olabi, Effects of post-weld heat-treatment soaking temperature on the mechanical properties and residual stresses of a martensite stainless-steel welded component, Journal of material Processing Technology, Volume 38, issue1-2 , : 387-398 (1993).

[14] Y.C. Lin, K.H. Lee ,Effect of preheating on the residual stress in type 304 stainless steel weldment*,* Journal of Materials Processing Technology, Volume 63, Issues 1-3,: 797-801(1997).

[15] C. P. Chou and Y. C. Lin **,**A new technique for reducing the residual stress induced by welding in type 304 stainless steel, Journal of materials processing technology, vol. 48, issue 1-4,: 693-698(1995).

[16] ASME, 2007, ASME Boiler & Pressure Vessel Code, Section II, Part D

[17] ASME Boiler & Pressure Vessel Code, Section VIII, Division 2.

[18] NBCC, 2005, National Building Code of Canada, Part 4, structural design.