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INTEGRAL MEAN OF YIELD CONCEPT APPLIED TO THERMAL HOT SPOTS - VALIDATION OF A LEVEL 2 DAMAGE ASSESSMENT METHOD

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ABSTRACT

The overall framework for a Level 2 assessment of local thermal hot spot in pressure vessels was first developed by Seshadri [1]. The assessment procedure invokes the concept of integral mean of yield and the concept on a reference volume to determine the reduction of load capacity caused by hot spot damage. This paper investigates the accuracy of this assessment by comparing the results of the Level 2 assessment with a Level 3 assessment (inelastic finite element analysis). Three examples with varying pressure component and hot spot sizes are considered. The comparison yielded a low variance between the Level 2 and Level 3 assessments with the Level 2 assessment being more conservative.

NOMENCLATURE

$2a$ = Length of hot spot in circumferential direction

$2b$ = Length of hot spot in longitudinal direction

c = Hot spot measured radial bulge

c_L = Calculated radial bulge limit

E = Weld joint efficiency from the original construction code, if unknown use 0.7

FCA = Specified future corrosion allowance

$LOSS$ = Metal loss in the shell prior to the assessment equal to the nominal (or furnished thickness if available) minus the measured minimum thickness at the time of the inspection

m_D = Limit load multiplier to be used in RSF for damage shell

m_u = Limit load multiplier for undamaged shell

m_D^0 = Upper bound multiplier for damaged shell

m_{LD} = Lower bound multiplier for damaged shell

$m_{\alpha D}$ = m-alpha limit load multiplier for damage shell

P_b = Local bending stress

P_{Design} = Internal design pressure

P_m = Global membrane stress

P_L = Local membrane stress

Q = Secondary stress

R = Inside radius of the cylindrical shell

R_C = $R + LOSS + FCA$

R_m = Mean radius of the cylindrical shell

RSF = Remaining strength factor

S_1 = Maximum principal stress

S_2 = Middle principal stress

S_3 = Minimum principal stress

S_D = Allowable Stress (damaged)

S_U = Allowable Stress (undamaged)

S_{yD} = Yield Strength (damaged)

S_{yU} = Yield strength (undamaged)

t = Shell wall thickness

t_c = $t - LOSS - FCA$

t_{sl} = Thickness required for supplemental load based on the longitudinal stress

V_D = Hot spot damaged volume

V_R = Reference volume

V_U = Undamaged volume

X_C = Decay length in circumferential direction

X_L = Decay length in longitudinal direction

ζ = Damage severity index

σ = Principal membrane stress or von–Mises stress calculated using applicable vessel code formula at design pressure

σ_L = Longitudinal stress

σ_θ = Circumferential stress

INTRODUCTION

Thermal hot spots are defined as regions on the pressure containing boundary where the surface temperature exceeds the surrounding material. They are typically caused by deterioration of internal refractory material or mal-distribution of internal fluid flow. Hot spots can be found through thermography and sometimes by visual inspection. At times, the hot spot temperature exceeds the design temperature of the pressure equipment.

In refineries and chemical plants, affected equipment and plants are hydrotreating and hydrocracking reactors, ammonia plants, cokers, catalytic reforming units, fluid catalytic cracking units, hydrogen manufacturing plants, gasification units, ethylene crackers and sulfur recovery units.

Given that hot spots are formed as a result of local deterioration of internal refractory, mal-distribution of process flow in fixed-bed reactors or abnormal reaction inside reactors, they must be monitored and mitigated, or they may lead to a local overstress condition which could result in permanent distortion of the pressure boundary, material property deterioration or even loss of containment. Conventional tactics in operating plants focuses on detection, mitigation, evaluation and monitoring of hot spots as a holistic approach to ensure pressure equipment integrity. Mitigation methods include various ways of applying external cooling locally over a hot spot. For reactors, variations of process parameters are often implemented to control local hot spots. Kraus [5], Bednar [6] and Seshadri [1] provided guidance in evaluation of hot spots in equipment. Beyond the scopes of these methods, hot spot evaluations in plants are now handled by finite element modelling. At the time of writing, API 579/ASME FFS Code committee is developing a dedicated section on hot spot evaluation. Development of this section is underway.

Adibi-Asl and Seshadri [2] extended the Level 2 assessment method to include evaluation beyond local hot spot. The assessment method calculates a remaining strength factor (RSF) that represents the reduction of load carrying capacity caused by the hot spot damage, using closed-form equations. This RSF is then used to calculate a new design pressure which would then be used to determine if the pressure vessel is fit for service with local hot spot damage. The proposed method is particularly suited for Level 2 assessment under the framework of API 579-1/ASME FFS-1.

Using finite element modelling technique, this paper compares the RSF calculated by the Seshadri's method versus the finite element modelling results. Three work examples with various hot spot sizes, t/D ratios, and the degrees of temperature excursion are considered.

LEVEL 2 HOT SPOT DAMAGE ASSESSMENT METHOD – SESHADRI [1] [1]

The Level 2 assessment evaluates the structural integrity of an in-service component containing thermal hot spots. It requires the dimension of the pressure component, material strength of the damaged [2] and undamaged component, size of the hot spot, and internal pressure.

This Level 2 assessment utilizes a concept of integral mean of yield. The concept refers to a reference volume that is "kinematically active" with the plastic action in the presence of the hot spot. It is a region where plastic dissipation is expected.

"*The remaining strength of a damaged component not only depends on the strength of the damaged area but is also dependent the neighboring undamaged area which plays a role in facilitating the severity of the damage via the edge effects near discontinuities. The affected area which includes damaged and neighboring undamaged region is called "reference volume"* [1]

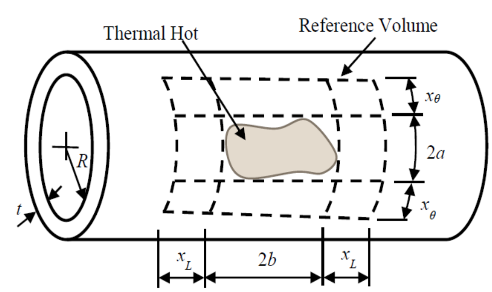


Figure 1 Reference volume dimensions for hot spot damage in cylindrical shell [2]

[1] In this paper, the term Seshadri method and Level 2 method are used interchangeably. Level 3 method and FEA method are also used interchangeably.

[2] The word damage in this paper simply means the area of a hot spot which is a flaw that requires fitness-for-service evaluation. It is an area where the temperature exceeds the original design temperature, but below the temperature beyond which metallurgical change is expected.

Decay length is defined as the distance at which a localized external or internal load affects the component. Area further away than the decay length is considered to experience negligible effect from the local external or internal load.

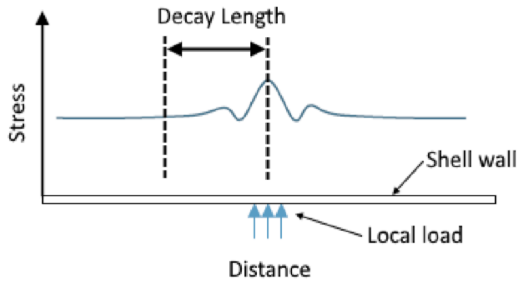


Figure 2 Schematic illustration of decay length

The dimensions of the reference volume are calculated based on the decay length around the hot spot, specifically:

$$V_R = V_U + V_D \quad \text{(Eqn. 1)}$$

$$V_D = (2a)(2b)t \quad \text{(Eqn. 2)}$$

$$V_R = 4t(a + X_C)(b + X_L) \quad \text{(Eqn. 3)}$$

$$V_U = V_R - V_D \quad \text{(Eqn. 4)}$$

Based on the list of information mentioned above, the Level 2 assessment calculates a RSF which Adibi-Asl and Seshadri [2] defined as follow:

$$RSF = \frac{Limit\ load\ multiplier\ of\ damaged\ shell}{Limit\ load\ multiplier\ of\ undamaged\ shell} \quad \text{(Eqn. 5)}$$

This RSF is used to calculate maximum allowable pressure the damaged component can withstand and indicates if the damaged component is fit for service.

Aside from the RSF calculation, a bulge limit is also established by the Level 2 assessment. Depending on the temperature, hot spot damage can cause bulging and plastic yielding at the hot spot. According Tantichattanont [7], the maximum membrane strain at the bulge is limited to 1%. The calculated bulge limit is checked against the FEA results to ensure the strain limit is met.

FINITE ELEMENT ANALYSIS (FEA) SETUP

The analyses are completed using ANSYS Mechanical General Purpose Finite Element Analysis software version 17.0. Limit Load Analysis Method [3] is employed for this study, which utilizes elastic-perfectly plastic (EPP) material models and small displacement theory. Yield strength for the EPP stress-strain curves are set based on the temperature dependent yield strength of the material, obtained from ASME Section II, Part D [8].

For the assessment of the bulging due to the hot spots, EPP stress-strain curves may result in erroneous displacement results. Separate analyses are therefore completed using temperature dependent strain hardening stress-strain curves generated per the MPC Stress-Strain Curve Model [4].

Definition of Hot Spot Sizing
For the hot spot implementation in the models, three different hot spot representations are considered:

i) Peak Temperature Model

The hot spot in the model is sized as the area from the thermography where the temperatures are the maximum temperature of the hot spot. See Figure below. This selected region in the model is considered damaged and the yield strength is reduced based on the peak hot spot temperature. The region outside the peak hot spot is considered undamaged and the yield strength is based on the normal surrounding wall temperature.

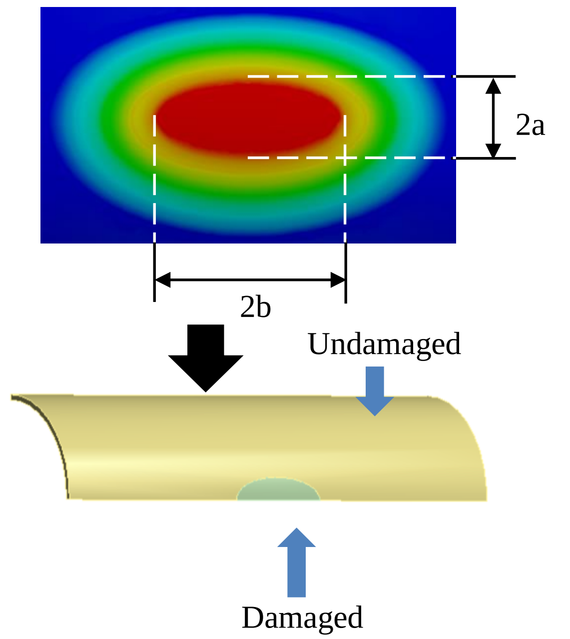


Figure 3 Peak temperature hot spot implementation

ii) Conservative Temperature Model (most conservative)
The entire extent of the hot spot and thermal gradient, which includes all area with temperature higher than the design temperature, is considered as the hot spot. The entire hot spot is also deemed to experience reduction of yield strength down to that of the material at the peak temperature. The region outside this entire hot spot extent is undamaged, retaining the yield strength of the material at the far-field temperature. (See Figure 4)

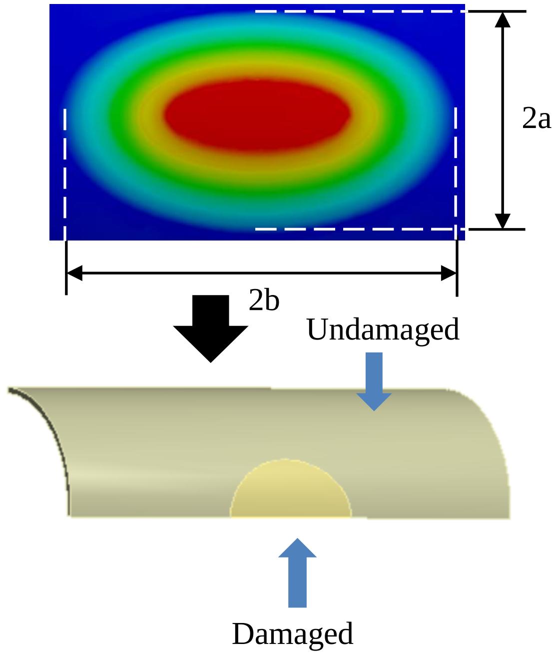


Figure 4 Conservative temperature hot spot implementation

iii) Real Temperature Model
Temperatures of the hot spot and resulting thermal gradient are input into a steady-state thermal analysis model based on the thermography data. The temperature dependent yield strength, Young's Modulus, thermal conductivity, and coefficient of thermal expansion are all included in the material model.

The RSF value calculated using this method cannot directly compare to Seshadri's method, as Seshadri's method only allows for one hotspot temperature.

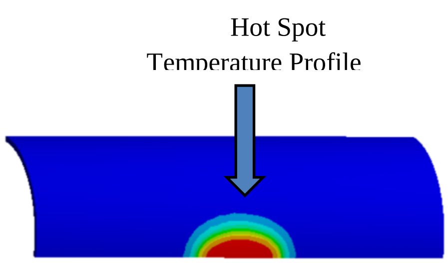


Figure 5 Real temperature hot spot implementation

WORKED EXAMPLES

Task 1 - Hydrogen Manufacturing Unit Transfer Header

Task 1 considers a chrome-moly transfer header in hydrogen manufacturing unit transfer header with internal refractory lining:

Outside Diameter: 914.4 mm

Wall Thickness: 24 mm

Material: SA-387, Grade 11, Class 2

Design Condition: 3.800 MPa at 200°C

Hot Spot Temperature: 315°C

Yield Strength Undamaged: 260 MPa at 200°C

Yield Strength Damaged: 240 MPa at 315°C

Based on the thermograph, the local hot spot reaches a maximum of 315°C (Figure 7). Two hot spots are analyzed with this model (2a x 2b):

Task 1a) 406 mm by 203 mm
Task 1b) 559 mm by 433 mm

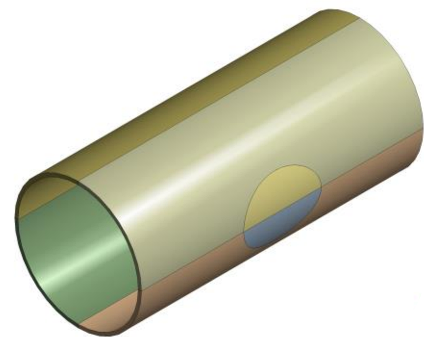


Figure 6 Hydrogen Manufacturing Unit Transfer Header Model

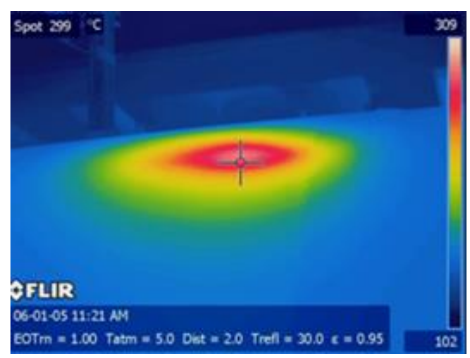
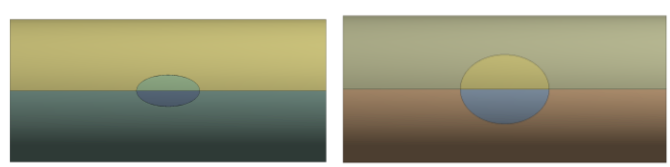


Figure 7 Thermography image of a hot spot located on the transfer header caused by deterioration of the internal refractory



a) b)

Figure 8 Front view of the hot spot on the transfer header model, a) 406 mm by 203 mm hot spot; b) 559 mm by 433 mm hot spot

Task 2 - De-sulfurization Reactor

The second work example considers a 1 1/4Cr-1/2Mo de-sulfurization reactor with the following parameters:

Outside Diameter: 3760 mm

Wall Thickness: 61 mm

Material: SA-387, Grade 11, Class 2

Design Condition: 5.171 MPa at 340°C

Hot Spot Temperature: 427°C

Yield Strength Undamaged: 238 MPa at 343°C

Yield Strength Damaged: 221 MPa at 427°F

Two hot spot sizes (2a x 2b) are analyzed with this model:

Task 2a) 1143 mm by 889 mm

Task 2b) 1829 mm by 1473 mm

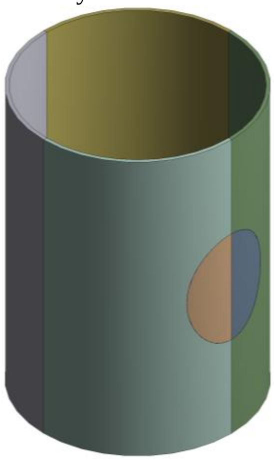
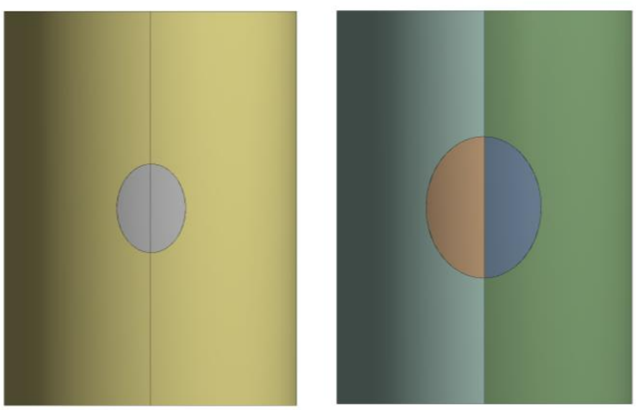


Figure 9 De-Sulfurization Reactor Model



a) b)

Figure 10 Front view of the hot spot on the de-sulfurization reactor model, a) 1143 mm by 889 mm hot spot; b) 1829 mm by 1473 mm hot spot

Task 3 - Catalyst Transfer Line

The third work example considers a cold-walled carbon steel catalyst transfer line with internal refractory lining:

Outside Diameter: 914.4 mm

Wall Thickness: 9.525 mm

Material: SA-516, Grade 70

Design Condition: 2.895 MPa at 148°F

Hot Spot Temperature: 371°C

Yield Strength Undamaged: 231 MPa at 148°C

Yield Strength Damaged: 187 MPa at 371°C

Two hot spot sizes (2a x 2b) are analyzed with this model:

Task 3a) 457 mm by 152 mm

Task 3b) 610 mm by 203 mm

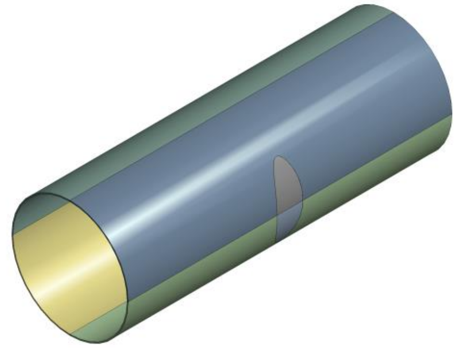
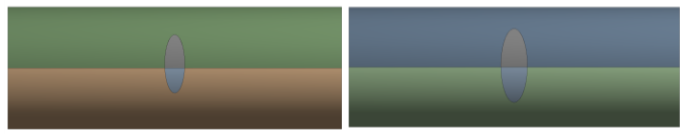


Figure 11 Catalyst Transfer Line Model



a) b)

Figure 12 Front view of the hot spot on the catalyst transfer line model, a) 457 mm by 152 mm hot spot; b) 610 mm by 203 mm hot spot;

LEVEL 2 CALCULATION ON HOT SPOTS

These hot spots are first evaluated with the Level 2 hot spot method. Task 3a is here described in details to demonstrate the Level 2 assessment method for a hot spot damaged cylinder under internal pressure. [2]

Task 3a: Catalyst Transfer Line
Material: SA-516 Grade 70
Diameter 914.4 mm, thickness 9.525 mm
Hot spot size: 457 mm by 152 mm

Input Data

Geometry Inputs

Cylindrical Shell:

$R = 447.675$ mm $t = 9.525$ mm

$t_{sl} = 0$ mm $E = 1.0$

$LOSS = 0$ mm $FCA = 0\ mm$

$c = 4.55$ mm

Hot Spot Dimensions:

$2a = 457$ mm $2b = 152$ mm

Material Inputs

Material: SA-516, Grade 70

Undamaged material @ 148°C

$$S_{yU} = 231\ MPa$$
$$S_U = 138\ MPa$$

Damaged @ 371°C

$$S_{yD} = 187\ MPa$$
$$S_D = 102\ MPa$$

Load Inputs

$$P_{Design} = 2.895\ MPa$$

Decay Lengths Calculation

$$X_L = 2.5\sqrt{Rt} = 2.5\sqrt{447.675 \times 9.525}$$
$$= 163.25\ mm$$
$$X_C = 6.3\sqrt{Rt} = 6.3\sqrt{447.675 \times 9.525}$$
$$= 411.39\ mm$$

Reference Volume Calculation

$$V_D = (2a)(2b)t = (457)(152)9.525$$
$$= 661645\ mm^3$$

$$V_R = 4t(a + X_C)(b + X_L)$$
$$= 4 \times 9.525(228.5 + 411.39)(76 + 163.25)$$
$$= 6106332\ mm^3$$

$$V_U = V_R - V_D = 6106332 - 661645$$
$$= 5444687\ mm^3$$

Damage Severity Index Calculation

$$\zeta = 0.25(\frac{a}{X_C}) + 0.75(\frac{b}{X_L})$$
$$= 0.25(\frac{228.5}{411.39}) + 0.75(\frac{76}{163.25})$$
$$= 0.488$$

Elastic Stress Calculation

$$\sigma_\theta = \frac{P}{E}\left(\frac{R}{t} + 0.6\right) = \frac{2.895}{1.0}\left(\frac{447.675}{9.525} + 0.6\right)$$
$$= 137.80\ MPa$$

$$\sigma_L = \frac{P}{2E}\left(\frac{R}{t} - 0.4\right) = \frac{2.895}{2 \times 1.0}\left(\frac{447.675}{9.525} - 0.4\right)$$
$$= 67.45\ MPa$$

$$\sigma = MAX(\sigma_L, \sigma_\theta)$$
$$= 137.80\ MPa$$

Limit Load Multipliers Calculation

$$m_u = \frac{s_{yU}}{\sigma} = \frac{231.70}{137.80} = 1.681$$

$$m_{LD} = \frac{s_{yD}}{\sigma} = \frac{187.54}{137.80} = 1.361$$

$$m_D^0 = \sqrt{\frac{S_{yU}^2\, V_U\ +\ S_{yD}^2\, V_D}{\sigma^2 V_R}}$$
$$= \sqrt{\frac{231.70^2 \times 5444687 + 187.54^2 \times 661645}{137.84^2 \times 6106332}}$$
$$= 1.649$$

$$A = \frac{m_D^0}{m_{LD}} = \frac{1.649}{1.361} = 1.212$$

$$m_{\alpha D} = \frac{2m_D^0\left[2A^2 + \sqrt{A(A-1)^2(2.414 - A)(A + 0.414)}\right]}{(A^2 - 0.236)(A^2 + 4.236)}$$
$$= \frac{2\times 1.647\left[2\times 1.212^2 + \sqrt{1.212(1.212-1)^2(2.414-1.212)(1.212+0.414)}\right]}{(1.212^2 - 0.236)(1.212^2 + 4.236)}$$
$$= 1.529$$

Since $\zeta < 1.0$,

$$m_D = (1 - \zeta)m_{\alpha D} + \zeta m_{LD}$$
$$= (1 - 0.488)1.529 + 0.488 \times 1.361$$
$$= 1.447$$

RSF Calculation

$$RSF = \frac{m_D}{m_U} = \frac{1.447}{1.681}$$
$$= 0.861$$

Since this result is below RSF of 0.9 [4], the hot spot needs to have mitigation in place. The options of mitigation include applying air or steam cooling, or derating the transfer line, because of the hot spot.

Bulge Limit Calculation

$$c_L = \left[\frac{(1.01ab)^\gamma - a^\gamma b^\gamma}{a^\gamma + b^\gamma}\right]^{1/\gamma}, \gamma = 1.585$$
$$= \left[\frac{(1.01\times 228.5\times 76)^{1.585} - 228.5^{1.585}\times 76^{1.585}}{228.5^{1.585} + 76^{1.585}}\right]^{1/1.585}$$
$$= 5.03\ mm$$

c (4.55 mm)≤c_L (5.03mm , therefore the bulging limit is satisfied.

Given these results, the transfer line design pressure may be de-rated to 2.77 MPa because of the hot spot.

LEVEL 2 RESULTS AND COMPARISON WITH FEA

After the completion of Task 1, it was noted that the Conservative Temperature Model in hot spot sizing resulted in the lower RSF, which generates the most conservative RSF results. Therefore, Task 2 and Task 3 are evaluated using only the Conservative Temperature Model as the method of defining the size of a hot spot.

RSF Results Comparison

The RSF calculated from Seshadri's method and FEA are listed in Table 1 for each Task. Figure 13 summarizes the RSF results comparing the Level 2 method to Level 3 method for all tasks performed.

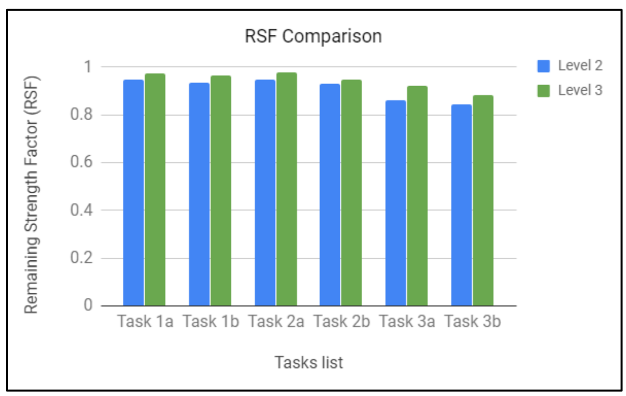


Figure 13 RSF comparison chart - Level 2 vs Level 3 FEA results

Table 1 RSF comparison between Seshadri's method and FEA

Task	Calculated RSF		Difference	Variance Percentage
	Level 2	Level 3 (FEA)		
1a	0.948	0.975	+0.027	+2.85%
1b	0.936	0.965	+0.029	+3.10%
2a	0.946	0.976	+0.030	+3.14%
2b	0.930	0.946	+0.016	+1.77%
3a	0.861	0.924	+0.063	+7.29%
3b	0.843	0.885	+0.042	+4.93%

For Task 1 and Task 2, the variance between Seshadri's method and the FEA results ranges from -0.21% to 7.29%. Overall, Seshadri's method (Level 2) produced RSF that are close to the FEA results, but always err on the conservative side.

The Real Temperature Model incorporates the thermal stress into the FEA. RSF's are calculated and shown below for reference. However, note in these worked examples, that the thermal stress does not contribute to the reduction of load capacity caused by the hot spot damage, using the API 579-1/ASME FFS-1 approaches.

Table 2 RSF from Seshadri's method, FEA without thermal load and FEA with real temperature model

Task	RSF calculated		
	Level 2	Level 3 (FEA)	Real Temperature Model (FEA)
1a	0.948	0.975	0.975
1b**	0.936	0.965	
2a**	0.946	0.976	0.982
2b**	0.930	0.946	0.965

** Conservative Model Sizing Method

In each of the three tasks, bulging limit check is performed on the Conservative Temperature Models. Using the elastic-plastic material stress-strain properties, the bulge displacement of the hot spot is calculated and compared to its limit from Seshadri's method.

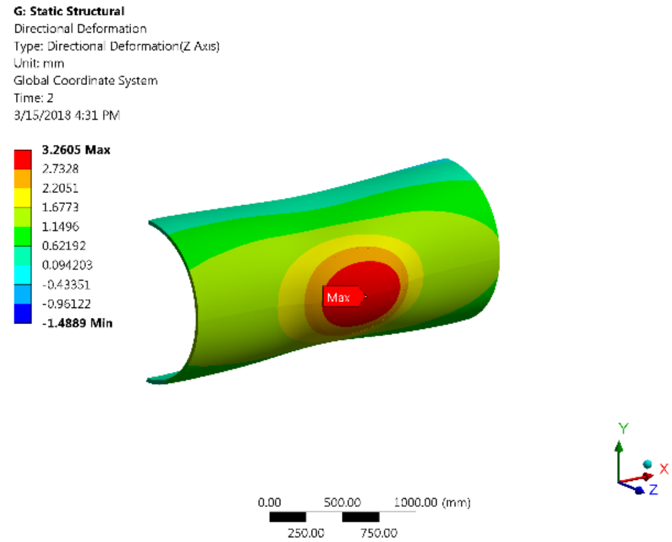


Figure 14 Task 1b bulge = 3.26 mm

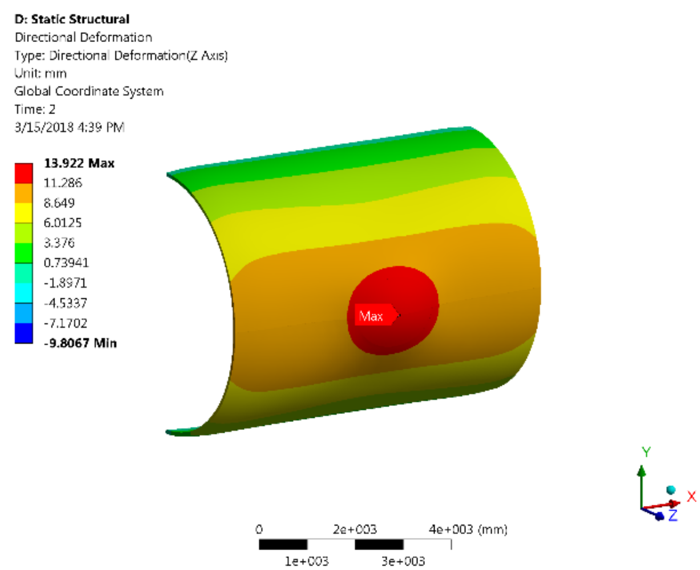


Figure 15 Task 2a bulge = 13.92 mm

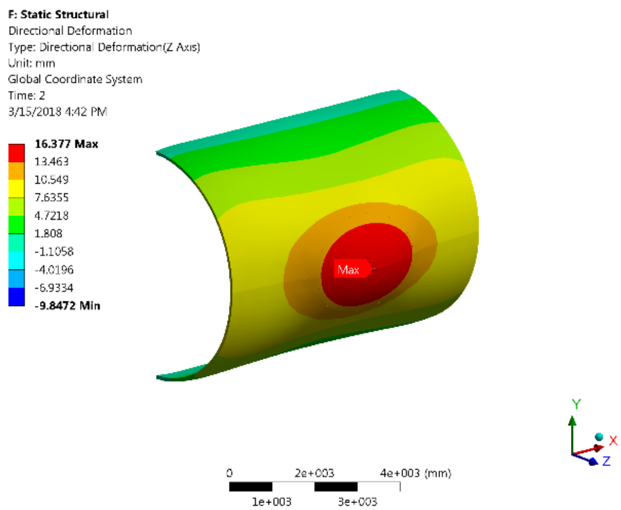


Figure 16 Task 2b bulge = 16.38 mm

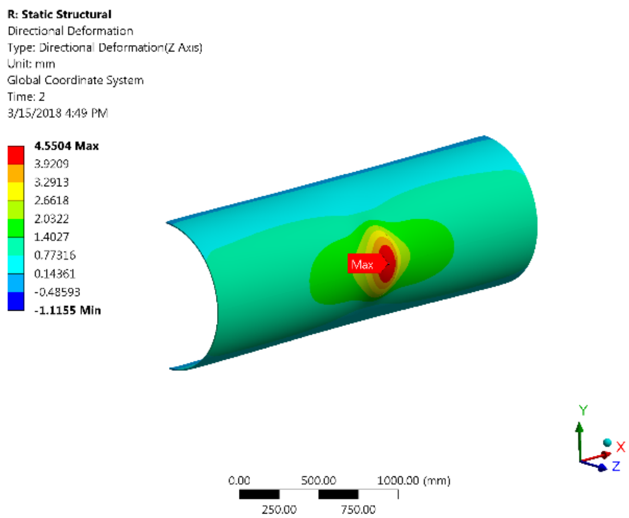


Figure 17 Task 3a bulge = 4.55 mm

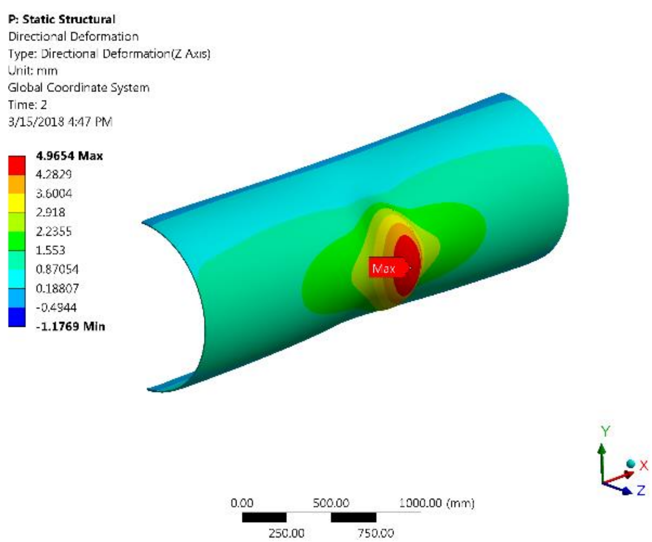


Figure 18 Task 3b bulge = 4.97 mm

Table 3 Summary of bulge limit checks

Task	FEA bulge results	Bulge Limit	Limit Check
1b	3.26 mm	11.48 mm	Pass
2a	13.92 mm	16.35 mm	Pass
2b	16.38 mm	38.51 mm	Pass
3a	4.55 mm	5.05 mm	Pass
3b	4.97 mm	6.73 mm	Pass

EFFECTS OF THERMAL STRESSES

For all the cases in Task 1 and Task 2, linear elastic material properties were used with the Real Temperature Model (actual thermal distribution). The hot spots models pass all the stress limits in all the stress categories listed in API 579-1/ASME FFS-1 [4], namely:

$$P_m < S \quad \text{(Eqn. 6)}$$
$$P_L + P_b < 1.5\,S \quad \text{(Eqn. 7)}$$
$$P_L + P_b + Q < 3\,S \quad \text{(Eqn. 8)}$$
$$S_1 + S_2 + S_3 < 4\,S \quad \text{(Eqn. 9)}$$

The elastic stress FEA result from Task 2b is listed below as an example to demonstrate the stress evaluation including the influence of thermal stresses.

The membrane (P_m/P_L) and bending (P_b) stresses generated from primary load and internal pressure, are checked for protection against plastic collapse:

$$P_m = 137\,MPa < S, 144\,MPa$$
$$P_L + P_b = 142\,MPa < 1.5S, 216\,MPa$$

The primary and secondary stress ($P_L + P_b + Q$) generated by the internal pressure and thermal gradient is checked for protection against ratcheting failure:

$$P_L + P_b + Q = 214\,MPa < 3S, 432\,MPa$$

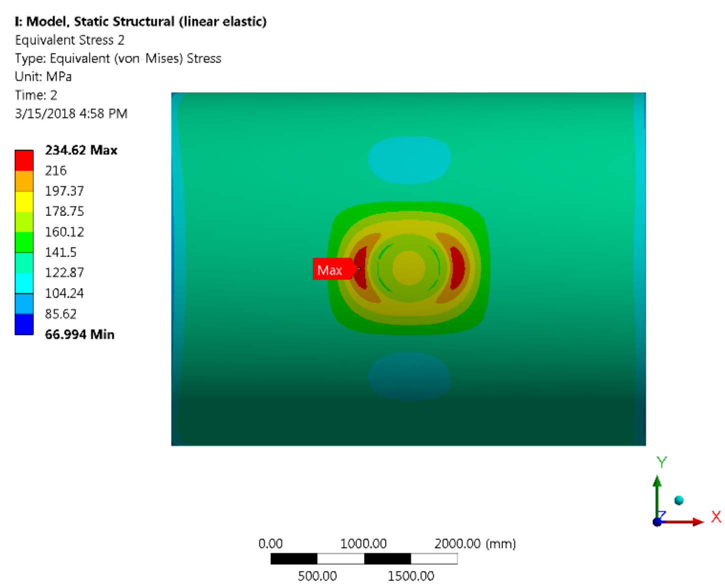


Figure 19 von-Mises stress plot including thermal stress

Lastly, the sum of the principal stresses generated from primary load, internal pressure, is checked for protection against local failure:

$$S_1 + S_2 + S_3 = 252\,MPa < 4S, 576\,MPa$$

For the tasks evaluated, the aspect ratios (a/b) of the hot spots range from 1.24 to 3.00. They pass the thermo-mechanical stress evaluation according to the Code rules.

CONCLUSIONS

A review has been performed on Seshadri's method to evaluate hot spots on pressure equipment at temperatures below the creep regime. The RSF is compared to the results generated from FEA. The comparison shows a very good correlation between the two analysis methods, variance ranges from 0.21% to 7.29%, with the proposed Level 2 method always yield a conservative result than the Level 3 FEA results.

When defining the size of a hot spot, from thermograph plot, the Conservative Temperature Model is recommended in this paper since it produces more conservative results. From the results in Task 2 (De-sulfurization Reactor) and Task 3 (Catalyst Transfer Line), it is also shown that the bigger the hotspot size, the more accurate Level 2 method predicts.

Seshadri's method assumes a hotspot is rectangular (2a x 2b) which inherently yields a conservative result when compared to real life hot spot scenario via FEA method. In conclusion, Seshadri's proposed method to evaluate hot spots on pressure equipment yields similar results as the FEA method, but it is more conservative.

The models in Task 1, Task 2, and Task 3 pass the checks in all the stress categories using linear elastic materials properties. Below the creep temperature regime and within the aspect ratio range, secondary stresses do not affect the primary load capacity in these examples.

Future enhancement of the Level 2 method in hot-spot evaluation may extend to creep temperatures regime and to the effect of large-displacement theory.

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