Level 3 Assessment as per API 579-1/ASME FFS-1 for Pressure Vessel General Metal Loss by using FEA Techniques.

By

Kingston Rivington

ASME Authorized Inspector (A, AR)

ASNT Level 3 RT, PT, MT, UT, VT, ET, LT

PAUT/TOFD level 3, API 510,570,653

rivington24@gmail.com

---

1. Introduction:

The Fitness-For-Service assessment for pressure vessel during its service subject to general metal loss or local metal loss resulting from corrosion, erosion, or combined condition .The FEA assessment can be used to ensure the integrity of a pressure retaining item for its continual safe operation as Level 1 and Level 2 assessment does not meet the criterion. In this example the thickness average approach has been chosen to provide better conservative result and assumed that the general metal loss occurred inside surface of pressure vessels based on point thickness reading and internal visual inspection. Thus If a more rigorous analysis is performed, no need for re-rate and alteration, saving repair cost or replacement cost and down time.

2. Mechanical Design for Condensate Recovery Drum as per ASME SEC.VIII, DIV.-1.ED 2004

.

Vessel Data

Material	SA 516 Gr 60 2004 Ed
Design Condition	4.35 Mpa
Design Temp	60 °C
Allow able stress for Temp	138 Mpa
Inside Diameter	1000 mm
Inside radius	500 mm
Nominal Thickness	20 mm
Future Corrosion Allowance	2 mm
Weld Joint Efficiency	1.0
Tangential distance (TL)	3000 mm

Internal corrosion (away from discontinuity) on the cylindrical shell of Condensate Recovery Drum has been found during off stream inspection.Details regarding the Condensate Recovery Drum and inspection data are given below. Determine if the Condensate Recovery Drum is suitable for continued operation.

Inspection Data

Based on a visual inspection, the corrosion loss is characterized as general, and point thickness readings has taken in 15 locations at shell location (see table E2-1)

Table E2-1

Location	Thickness Reading *t, mm*
1	17
2	16
3	15
4	17
5	14
6	16
7	15
8	17
9	18
10	17
11	15
12	17
13	17
14	18
15	18

3.0 Level 1 Assessment

(Assessment for internal pressure per paragraph - 4.4.2)

STEPS 1 - Use the point thickness readings Table E2.1 shown above; and determine the minimum measured thickness, $t_{min.}$, the average measured thickness, t_{am}, and the Variation, COV.

Where,

COV -Coefficient of Variation.

LOSS -Uniform metal loss away from the damage area at the time of the inspection. *LOSS*

$t_{am.}$ -Average measured wall thickness of the component based on the point thickness readings (PTR) measured at the time of the inspection.

$t_{min.}$ -minimum required wall thickness of the component.

Table E3-1

Location	Thickness Reading **$t_{rd,i}$ = 1 to N**	**$t_{rd,i} - t_{am}$**	**$(t_{rd,i} - t_{am})^2$**
1	17	0.5333	0.2844
2	16	-0.4667	0.2178
3	15	-1.4667	2.1511
4	17	0.5333	0.2844
5	14	-2.4667	6.0844
6	16	-0.0667	0.0044
7	15	-1.4667	2.1511
8	17	0.5333	0.2844
9	18	1.5333	2.3511
10	17	0.9333	0.8710
11	15	-1.4667	2.1511
12	17	0.5333	0.2844
13	17	0.5333	0.2844
14	18	1.5333	2.3511
15	18	1.5333	2.3511
	$t_{am} = \frac{1}{N}\sum_{i=1}^{N} t_{rd,i}$ =**16.4667**	$S = \sum_{i=1}^{N}(t_{rd,i} - t_{am})^2 =$	**22.1066**
$COV = \frac{1}{t_{am}}\left[\frac{S}{N-1}\right]^{0.5}$ **=0.076**		**7.6%**	Use Average Thickness Method (tam)

STEP 2 – The COV equals 7.6%, which is less than 10%; therefore, the average thickness to be used in the calculation is the average thickness of the thickness distribution, or

t_{am} =16.4667

LOSS= $t_{nom.} - t_{am}$

= 20.0-16.4667

= 3.5333 mm

STEP 3 – Calculate the minimum required thickness

$t_{cir.}$ = PR/(SE − 0.6 P)

= 4.35(500+2+3.5333)/138(1.0)-0.6(4.35)

=16.24 mm

$t_{long.}$ = PR/(2SE + 0.4P)

= 4.35(500+2+3.5333)/2 *138(1.0)+0.4(4.35)

=7.91 mm

t_{min} = Max { t_{cir}, $t_{long.}$}

= Max {16.24, 7.91}

= 16.24 mm

STEP 4 – Determine if the component is acceptable for continued operation. Perform a Level 1assessment using Table 4.4 of API 579-1

(t_{am} − FCA) ≥ (t_{min})

(t_{am} − FCA) = (16.4667-2.0) ≥ 16.24

= 14.4667 ≥ 16.24 mm **FALSE**

Alternatively, the maximum allowable working pressure MAWP based on the average thickness (t_{am}) can be compared to the design pressure with the design pressure as the criterion.

t = t_{am} – FCA = 16.4667-2.0 = 14.4667

MAWP = SEt/(R+FCA+LOSS+0.6t)

= 138*1*14.4467/((500+2+3.5333+06*14.4467

= 3.88 Mpa

Condition is MAWP > Pd

3.88 >4.35 **FALSE**

The Level 1 assessment criteria are not satisfied

4.0 Level 2 Assessment

Perform a Level 2 assessment for internal pressure using Table 4.4. Of API 579-1

RSFa (Allowable Remaining Strength Factor) = 0.9 from 2F.2 of API 579

Condition is (t_{am} − FCA) ≥ (RSFa * t_{min})

(16.4667-2.0) ≥ (0.9*16.24)

14.4667 ≥14.616 **FALSE**

Alternatively, the maximum allowable working pressure (MAWP) based on the average thickness (tam)the criterion can be compared to the design pressure with the design pressure as below,

t = (tam-FCA)/RSFa = (16.4667-2.0)/0.9 =16.074

MAWP = SEt/(R+FCA+LOSS+0.6t)

= 138*1*16.074/(500+2+3.5333+06*16.074)

= 4.31 Mpa

Condition is MAWP > Pd

4.31 >4.35 **FALSE**

The Level 2 assessment criteria are not satisfied.

Now the Possibilities are Level 3 FEA assessments, Re-rate, Repair and Retire.

4.0 Level 3 Assessments.

For Level 3 Assessment, the stress analysis techniques stated in Annex 2D of API 579-1 has been utilized to evaluate regions of local metal loss at Condensate Recovery Drum .The finite element method (ANSYS software) was typically used to compute the stresses in corroded location. The evaluation carried based on a linear stress analysis with acceptability determined using stress categorization and stress linearization as per ASME Section VIII Div.2 part 5 and non-linear stress analysis with acceptability determined using a plastic collapse load. The thickness data was used directly in finite element model of the component. (as per table E.1.1)

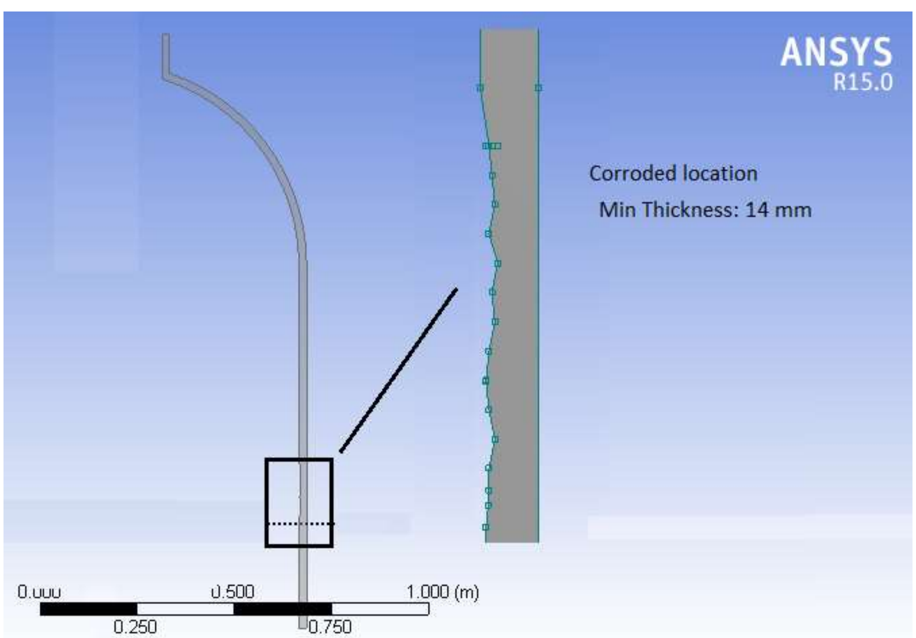

Figure 1 Vessel Shell Geometry with local corroded portion

4.1-Protection against Elastic Stress Analysis and Local Failure

The Elastic Stress Analysis and Local Failure Evaluation were carried at corroded area of shell location for compliance with respect to the elastic stress analysis criteria for plastic collapse and local failure as per guidance provided in ASME Sec VIII Div 2 part 5.2.2 and 5.3.2 .Internal pressure is the only load that was considered with respect its axial thrust pressure in the nozzle location. Other loading conditions are considered negligible.

STEP A – To find out the types of loads acting on the corroded area for fitness for assessment, In general, separate load cases are analyzed to evaluate "load-controlled" loads such as pressure and externally applied reactions due to weight effects and "strain-controlled" loads resulting from thermal gradients (not applicable here) and imposed displacements(not applicable here) The loads to be considered in the assessment shall include, but not be limited to, those given in Table 5.1 of ASME Section VIII Div 2 The load combinations that shall be considered for each loading condition shall include, but not be limited to those given in Table 5.3 of ASME Section VIII Div 2.

The only load considered is internal pressure of 4.35 Mpa and axial thrust pressure of 20.71 Mpa.

1) The finite element model has been developed in Ansys Mechanical APDL version 15.

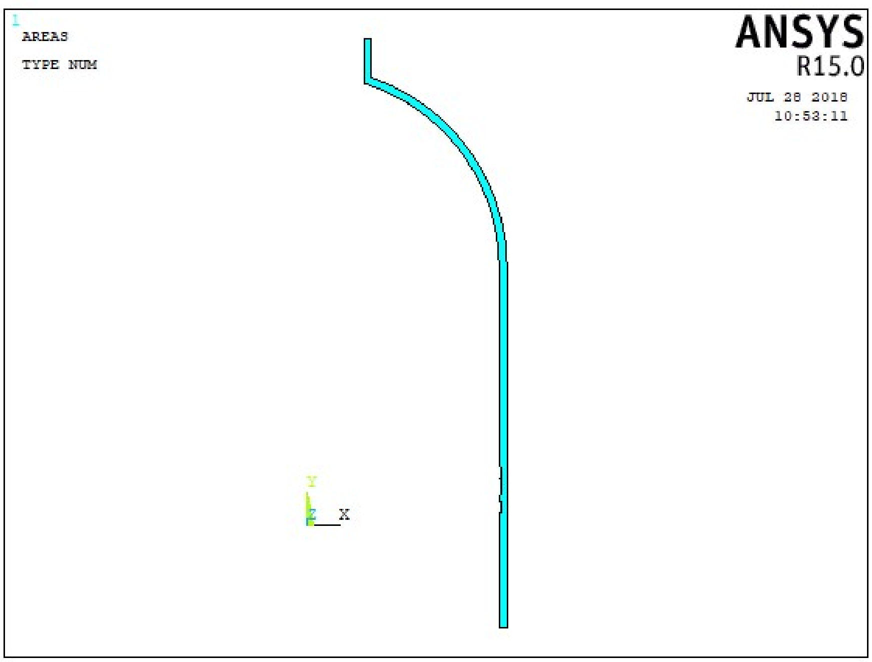

Figure 2 Axisymmetric FE Model

2) Due to symmetry in geometry and loading, an axisymmetric solid model is generated. To capture proper membrane behavior in the model the shell was extended a distance of 5 $\sqrt{Rt}$ below the head to shell transition. The FE model is illustrated in Figure 2. The model was generated with the ANSYS commercial FEA program, version 15.0.

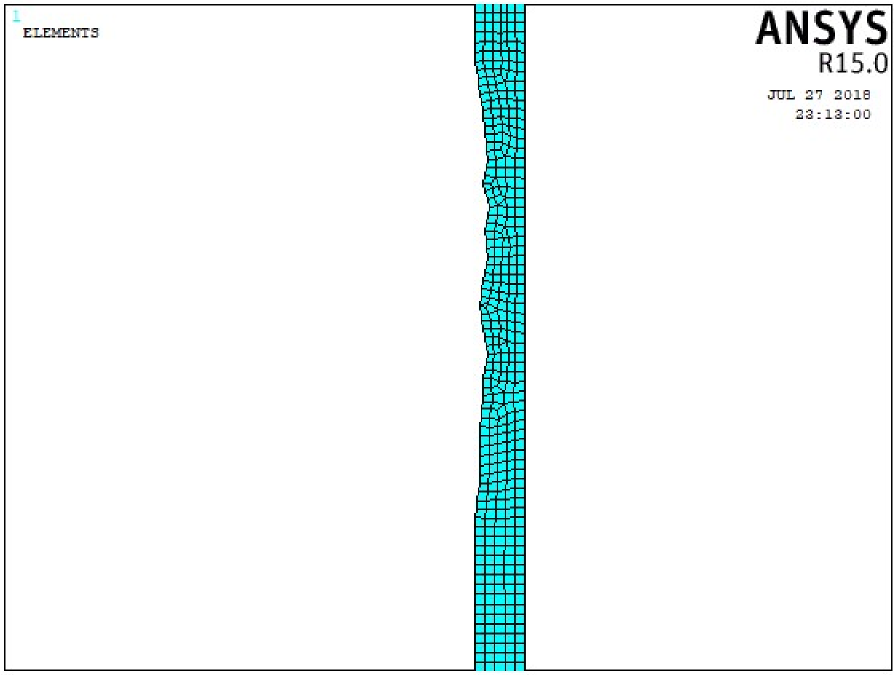

Figure 3 Meshing of Corroded location

3). The Element TYPE 1 PLANE 182 /SOLID /QUAD 4 NODE182 /Full integration was chosen to drive FE solution and generated mesh.

4) Apply the material properties given below to the appropriate components of the model.Material assignments are below,

Material Table

Component	Material	Young's Modulus	Poisson Ratio
Head	SA-516-70N	1.98 E+05	0.3
Shell	SA-516-70N	1.98 E+05	0.3

.

5) Apply the internal pressure load to the pressure boundaries of the vessel and an appropriate pressure thrust load to the nozzle. Applied the appropriate boundary conditions to the shell edge as per the figure 4.0 below.

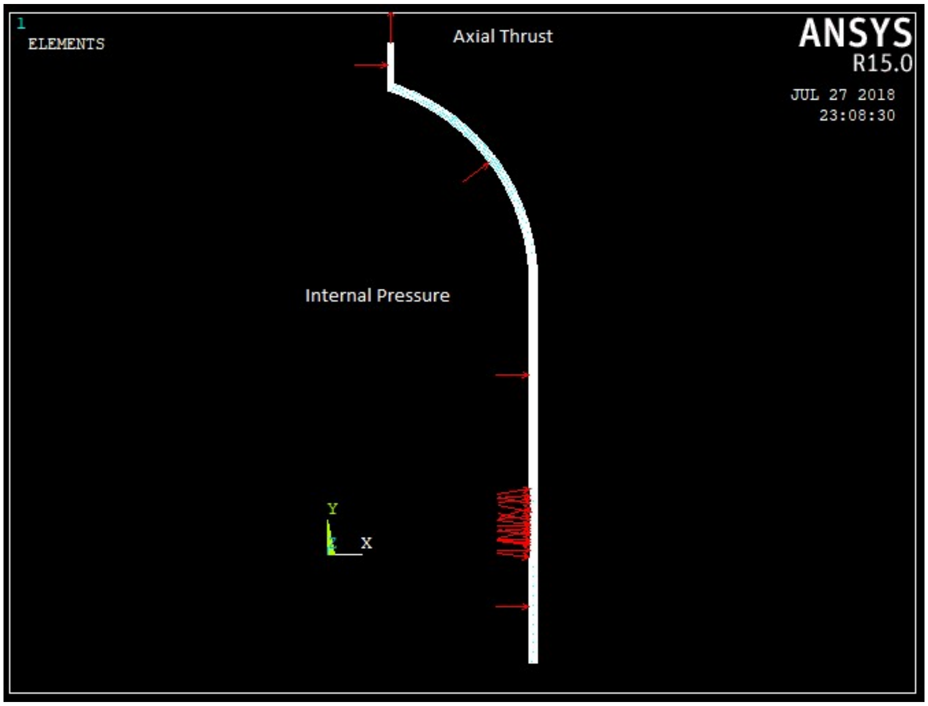

Figure 4. Load and Boundary Conditions for the FE Model

6). Run analysis and reviewed results for Deformation and Von mises equivalent stress below figure 5&6.

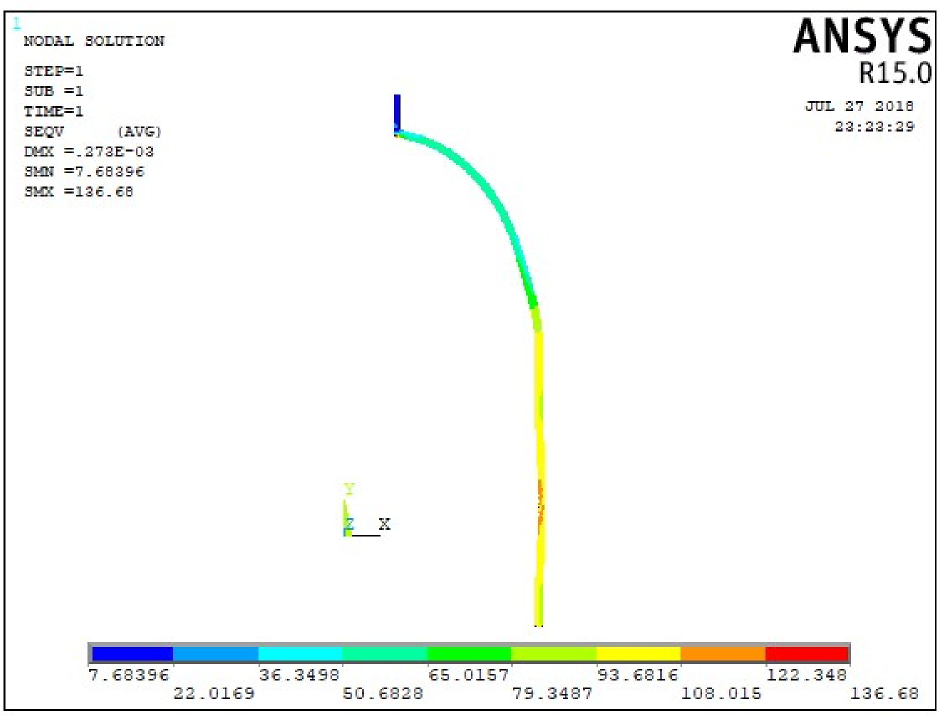

Figure 5. Results of Elastic Analysis, Von Mises Stress in Deformed States

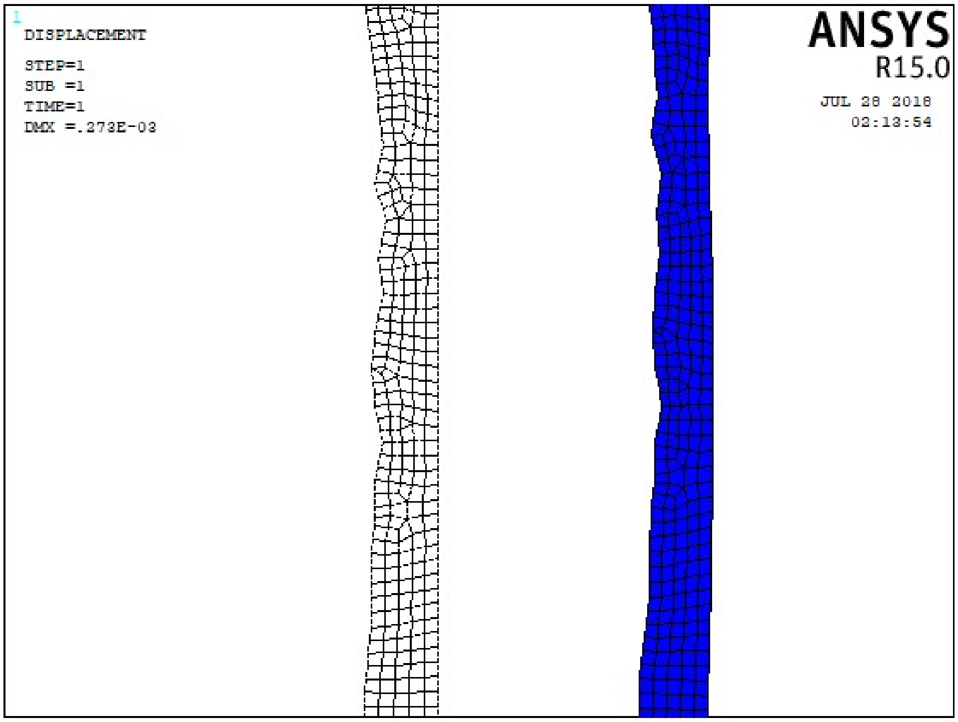

Figure 6. Results of Elastic Analysis, Total Deformation

STEP b) The Through wall stress linearization (Figure7&8) were conducted at corroded areas in the shell location to provide data for assessment. The resultant von Misses stresses for Pm, PL, and Pb stress categories are summarized in Table E 4.1

1. Placed proper stress tensor to an appropriate category for a component obtained by using ASME section VIII div. 2 Figure 5.1 and Table 5.6.Note that the equivalent stresses Q and F do not need to be determined to evaluate protection against plastic collapse.

i) *General primary membrane equivalent stress (Pm) -Average stresses across the thickness at any region away from discontinuities.*
ii) *Local primary membrane equivalent stress (PL) - Include the effect of discontinuities.*
iii) *Primary bending equivalent stress –(Pb) component of primary stress excluding discontinuities*
iv) *Secondary equivalent stress – (Q) Secondary membrane and bending.*
v) *Peak Stress (F)-Additional equivalent stress produced by a stress concentration or a thermal stress over and above the nominal (P +Q) stress level.*

2. Sum the stress tensors (stresses are added on a component basis) assigned to each equivalent stress category. The final result is a stress tensor representing the effects of all the loads assigned to each equivalent stress category.

3. The Pm equivalent stresses occur away from the head to shell junction, and PL and PL + Pb +Q equivalent stresses occur at the junction.

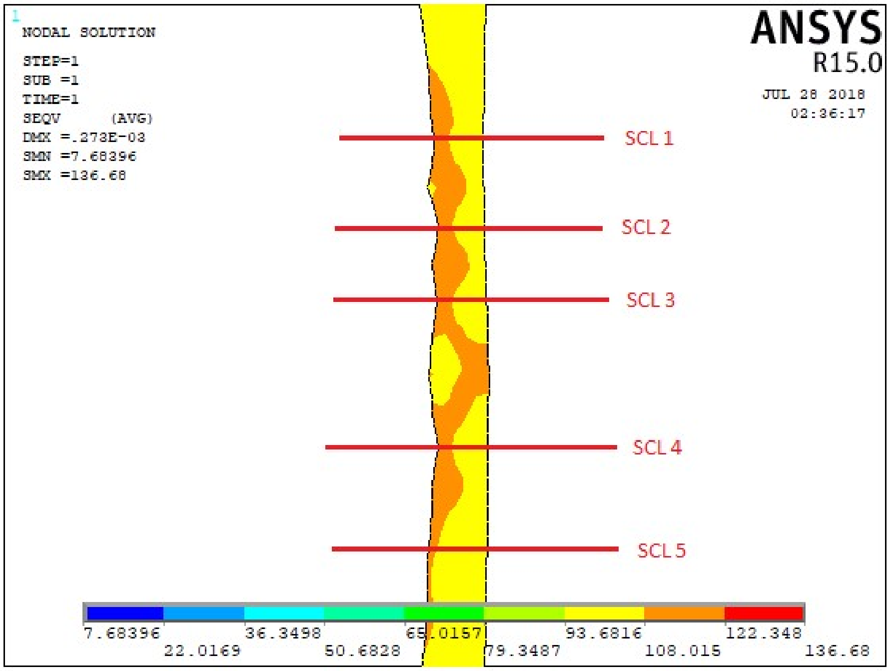

Figure 7. Stress Classification Lines (SCLs) in the corroded location.

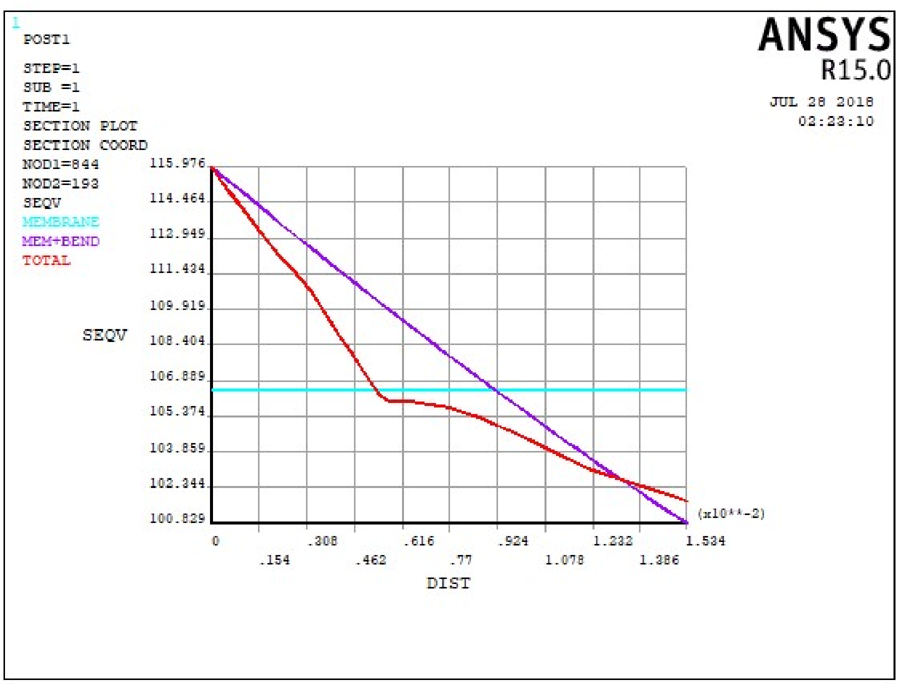

Figure 8. Stress distribution at corroded location

4. To evaluate protection against plastic collapse and local failure, compare the computed equivalent stress to their corresponding allowable values. See Table E4.1 for evaluation results.

(i)For protection against plastic collapse for Elastic Analysis

Pm ≤Sm

PL≤1.5Sm

PL+Pb≤1.5Sm

(ii)For protection against local failure (only corroded area).

σ 1+ σ 2+ σ 3 ≤ 4Sm

Here, σ the algebraic sum of the three linearized primary principal stresses from Design Load Combination.

As per API 579-1, 2D. 3.2, the assessment procedures for the Elastic Analysis of local failure shall be in accordance with VIII-2, Part 5, paragraph 5.3.2 except the acceptance criterion may be 4S/RSFa rather than 4S (lenient than ASME Sec.VIII Div.2)

4S/RSFa = 4*138/0.9

= 613.33 Mpa

Table E4.1- Results of the Elastic Analysis and local failure Criterion from ASME Section VIII, Div 2, Part 5

SCL No	Sm	Equivalent Linearized Stresses			Stress Evaluation			Local failure (Triaxial Stress)	Remarks
		Pm	Pl	Pb	Pm ≤Sm	PL≤1.5Sm	PL+Pb≤1.5Sm	σ 1+ σ 2+ σ 3 ≤ 4Sm	
1	138	106.7	NA	NA	Pass	NA	NA	(193.10≤613.33) Pass	Shell (away from discon.)
2	138	106.8	NA	NA	Pass	NA	NA	(200.25≤613.33) Pass	Shell (away from discon.)
3	138	107.6	NA	NA	Pass	NA	NA	(193.48≤613.33Pass	Shell (away from discon.)
4	138	107.0	NA	NA	Pass	NA	NA	(195.91≤613.33) Pass	Shell (away from discon.)
5	138	107.1	NA	NA	Pass	NA	NA	(182.37≤613.33) Pass	Shell (away from discon.)

```
PRINT LINEARIZED STRESS THROUGH A SECTION DEFINED BY PATH= SCL1   DSYS=  0

  RADIUS OF CURVATURE =   508.00

***** POST1 LINEARIZED STRESS LISTING *****
        INSIDE NODE =    842     OUTSIDE NODE =    192

 LOAD STEP     1  SUBSTEP=     1
 TIME=    1.0000         LOAD CASE=  0
```

```
 ** AXISYMMETRIC OPTION **     RHO =   508.00
 THE FOLLOWING X,Y,Z STRESSES ARE IN SECTION COORDINATES.

              ** MEMBRANE **
      SX           SY           SZ          SXY          SYZ          SXZ
 -0.2228       70.93        122.4      -0.3525       0.000        0.000
      S1           S2           S3          SINT         SEQV
   122.4       70.93      -0.2245       122.7        106.7

              ** BENDING **  I=INSIDE C=CENTER O=OUTSIDE
      SX           SY           SZ          SXY          SYZ          SXZ
 I  -4.336       11.97        4.856        0.000        0.000        0.000
 C  -1.888      0.5809E-01  0.2389E-04    0.000        0.000        0.000
 O  0.5598      -11.86       -4.856        0.000        0.000        0.000
      S1           S2           S3          SINT         SEQV
 I   11.97       4.856       -4.336        16.31        14.16
 C  0.5809E-01  0.2389E-04  -1.888        1.946        1.918
 O  0.5598      -4.856       -11.86        12.41        10.78

** MEMBRANE PLUS BENDING **  I=INSIDE C=CENTER O=OUTSIDE
      SX           SY           SZ          SXY          SYZ          SXZ
 I  -4.559       82.90        127.3      -0.3525       0.000        0.000
 C  -2.111       70.99        122.4      -0.3525       0.000        0.000
 O  0.3370       59.07        117.6      -0.3525       0.000        0.000
      S1           S2           S3          SINT         SEQV
 I   127.3       82.90       -4.560        131.8        116.2
 C   122.4       70.99       -2.112        124.5        108.4
 O   117.6       59.07       0.3349        117.2        101.5

  ** PEAK **  I=INSIDE C=CENTER O=OUTSIDE
      SX           SY           SZ          SXY          SYZ          SXZ
 I   0.000       7.467       -1.892        3.497        0.000        0.000
 C   2.121      -2.474      -0.7519      -0.9831       0.000        0.000
 O -0.1110E-15   3.716        1.067       0.1691       0.000        0.000
      S1           S2           S3          SINT         SEQV
 I   8.848      -1.382       -1.892        10.74        10.49
 C   2.322     -0.7519       -2.675        4.998        4.366
 O   3.723       1.067      -0.7682E-02   3.731        3.326

** TOTAL **  I=INSIDE C=CENTER O=OUTSIDE
      SX           SY           SZ          SXY             SYZ       SXZ
 I  -4.559       90.37        125.4        3.144        0.000        0.000
 C  0.1018E-01   68.51        121.7       -1.336        0.000        0.000
 O  0.3370       62.79        118.6      -0.1834        0.000        0.000
      S1           S2           S3          SINT         SEQV         TEMP
 I   125.4       90.47       -4.663        130.1        116.6        0.000
 C   121.7       68.54      -0.1585E-01   121.7        105.7
 O   118.6       62.79       0.3365        118.3        102.5        0.000

 PRINT LINEARIZED STRESS THROUGH A SECTION DEFINED BY PATH= SCL2   DSYS=  0
```

```
  RADIUS OF CURVATURE =   508.00

         ***** POST1 LINEARIZED STRESS LISTING *****
        INSIDE NODE =    848     OUTSIDE NODE =    187

 LOAD STEP     1  SUBSTEP=     1
 TIME=    1.0000         LOAD CASE=  0

** AXISYMMETRIC OPTION **     RHO =   508.00
THE FOLLOWING X,Y,Z STRESSES ARE IN SECTION COORDINATES.

             ** MEMBRANE **
     SX          SY          SZ          SXY         SYZ         SXZ
  1.349       75.11       123.8      0.3591       0.000       0.000
     S1          S2          S3          SINT        SEQV
  123.8       75.11       1.348       122.5       106.8

             ** BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I  -5.948       18.42       5.632       0.000       0.000       0.000
C  -3.154      0.8342E-01  0.2587E-04   0.000       0.000       0.000
O -0.3606      -18.26      -5.632       0.000       0.000       0.000
     S1          S2          S3          SINT        SEQV
I   18.42       5.632      -5.948       24.37       21.11
C  0.8342E-01  0.2587E-04  -3.154       3.238       3.197
O -0.3606      -5.632      -18.26       17.90       15.93

             ** MEMBRANE PLUS BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I  -4.598       93.53       129.4      0.3591       0.000       0.000
C  -1.805       75.19       123.8      0.3591       0.000       0.000
O  0.9887       56.85       118.2      0.3591       0.000       0.000
     S1          S2          S3          SINT        SEQV
I   129.4       93.53      -4.600       134.0       120.2
C   123.8       75.19      -1.806       125.6       109.7
O   118.2       56.85      0.9864       117.2       101.5

             ** PEAK **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I   0.000       14.86      -3.181      -3.988       0.000       0.000
C   4.325      -4.340     -0.6394      0.4178       0.000       0.000
O  0.1110E-15   6.110       1.070      0.5783       0.000       0.000
     S1          S2          S3          SINT        SEQV
I   15.86      -1.003      -3.181       19.04       18.05
C   4.346     -0.6394      -4.360       8.705       7.566
O   6.165       1.070     -0.5424E-01   6.219       5.740

             ** TOTAL **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I  -4.598       108.4       126.3      -3.629       0.000       0.000
```

```
C   2.521       70.85       123.2      0.7769       0.000       0.000
O  0.9887       62.96       119.3      0.9373       0.000       0.000
     S1          S2          S3          SINT        SEQV        TEMP
I   126.3       108.5      -4.715       131.0       123.1       0.000
C   123.2       70.86       2.512       120.7       104.8
O   119.3       62.98      0.9746       118.3       102.5       0.000
```

PRINT LINEARIZED STRESS THROUGH A SECTION DEFINED BY PATH= SCL3   DSYS= 0

```
   RADIUS OF CURVATURE =   508.00

          ***** POST1 LINEARIZED STRESS LISTING *****
         INSIDE NODE =    854     OUTSIDE NODE =    182

  LOAD STEP     1  SUBSTEP=     1
  TIME=    1.0000         LOAD CASE=  0

 ** AXISYMMETRIC OPTION **     RHO =   508.00
 THE FOLLOWING X,Y,Z STRESSES ARE IN SECTION COORDINATES.

             ** MEMBRANE **
     SX          SY          SZ          SXY         SYZ         SXZ
 -0.1018       70.79       123.7       1.861       0.000       0.000
     S1          S2          S3          SINT        SEQV
   123.7       70.84     -0.1507       123.8       107.6

             ** BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
 I  -3.737       4.045       3.082       0.000       0.000       0.000
 C  -1.832      0.1963E-01  0.1517E-04   0.000       0.000       0.000
 O  0.7277E-01  -4.005      -3.082       0.000       0.000       0.000
     S1          S2          S3          SINT        SEQV
 I   4.045       3.082      -3.737       7.781       7.347
 C  0.1963E-01  0.1517E-04  -1.832       1.852       1.842
 O  0.7277E-01  -3.082      -4.005       4.078       3.704

             ** MEMBRANE PLUS BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
 I  -3.839       74.84       126.8       1.861       0.000       0.000
 C  -1.934       70.81       123.7       1.861       0.000       0.000
 O -0.2908E-01   66.79       120.6       1.861       0.000       0.000
     S1          S2          S3          SINT        SEQV
 I   126.8       74.88      -3.883       130.6       113.9
 C   123.7       70.86      -1.981       125.7       109.3
 O   120.6       66.84     -0.8088E-01   120.7       104.7

             ** PEAK **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
 I   0.000       8.414      -1.138       3.250       0.000       0.000
 C   2.273      -2.268     -0.5571     -0.6180       0.000       0.000
 O  0.3469E-17   2.955      0.6652     -0.6249       0.000       0.000
```

```
     S1          S2          S3          SINT        SEQV
 I   9.523      -1.109      -1.138       10.66       10.65
 C   2.356      -0.5571     -2.351       4.707       4.115
 O   3.082       0.6652     -0.1267      3.209       2.895

              ** TOTAL **   I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
 I  -3.839       83.25       125.6       5.111       0.000       0.000
 C  0.3396       68.54       123.1       1.243       0.000       0.000
 O -0.2908E-01   69.74       121.3       1.236       0.000       0.000
     S1          S2          S3          SINT        SEQV        TEMP
 I   125.6       83.55      -4.138       129.8       114.7       0.000
 C   123.1       68.57       0.3170      122.8       106.6
 O   121.3       69.77      -0.5098E-01  121.3       105.5       0.000

PRINT LINEARIZED STRESS THROUGH A SECTION DEFINED BY PATH= SCL4   DSYS=  0

  RADIUS OF CURVATURE =   508.00

        ***** POST1 LINEARIZED STRESS LISTING *****
       INSIDE NODE =      2     OUTSIDE NODE =    172

 LOAD STEP     1  SUBSTEP=     1
 TIME=    1.0000          LOAD CASE=  0

** AXISYMMETRIC OPTION **     RHO =   508.00
THE FOLLOWING X,Y,Z STRESSES ARE IN SECTION COORDINATES.

             ** MEMBRANE **
     SX          SY          SZ          SXY         SYZ         SXZ
  1.220       70.40       124.3       3.239       0.000       0.000
     S1          S2          S3          SINT        SEQV
  124.3       70.55       1.069       123.2       107.0

             ** BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I  -5.496       12.36       5.285       0.000       0.000       0.000
C  -3.027      0.5998E-01  0.2602E-04   0.000       0.000       0.000
O -0.5582      -12.24      -5.285       0.000       0.000       0.000
     S1          S2          S3          SINT        SEQV
I   12.36       5.285      -5.496       17.85       15.57
C  0.5998E-01  0.2602E-04  -3.027       3.087       3.058
O -0.5582      -5.285      -12.24       11.68       10.17

             ** MEMBRANE PLUS BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I  -4.276       82.76       129.5       3.239       0.000       0.000
C  -1.807       70.46       124.3       3.239       0.000       0.000
O  0.6620       58.17       119.0       3.239       0.000       0.000
     S1          S2          S3          SINT        SEQV
```

```
I   129.5       82.88      -4.396       133.9       117.8
C   124.3       70.61      -1.952       126.2       109.7
O   119.0       58.35      0.4801       118.5       102.6

             ** PEAK **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I -0.8882E-15   13.08      -1.903      0.6734       0.000       0.000
C   3.754      -3.549     -0.7228      0.3267       0.000       0.000
O  0.3331E-15   5.040       1.375     -0.7196       0.000       0.000
     S1          S2          S3          SINT        SEQV
I   13.12     -0.3457E-01  -1.903       15.02       14.18
C   3.769     -0.7228      -3.564       7.333       6.404
O   5.141       1.375     -0.1007       5.242       4.682

             ** TOTAL **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I  -4.276       95.84       127.6       3.912       0.000       0.000
C   1.947       66.91       123.5       3.566       0.000       0.000
O  0.6620       63.21       120.3       2.520       0.000       0.000
     S1          S2          S3          SINT        SEQV        TEMP
I   127.6       95.99      -4.429       132.1       119.4       0.000
C   123.5       67.11       1.752       121.8       105.6
PRINT LINEARIZED STRESS THROUGH A SECTION DEFINED BY PATH= SCL5       DSYS=  0

  RADIUS OF CURVATURE =   508.00

         ***** POST1 LINEARIZED STRESS LISTING *****
        INSIDE NODE =      8     OUTSIDE NODE =    167

 LOAD STEP     1  SUBSTEP=     1
 TIME=    1.0000         LOAD CASE=  0

** AXISYMMETRIC OPTION **     RHO =   508.00
THE FOLLOWING X,Y,Z STRESSES ARE IN SECTION COORDINATES.

             ** MEMBRANE **
     SX          SY          SZ          SXY         SYZ         SXZ
 -1.573       62.45       121.5      -5.920       0.000       0.000
     S1          S2          S3          SINT        SEQV
  121.5       62.99      -2.116       123.6       107.1

             ** BENDING **  I=INSIDE C=CENTER O=OUTSIDE
     SX          SY          SZ          SXY         SYZ         SXZ
I  -2.048      -2.246       1.440       0.000       0.000       0.000
C -0.1309     -0.1237E-01  0.8078E-05   0.000       0.000       0.000
O   1.786       2.221      -1.440       0.000       0.000       0.000
     S1          S2          S3          SINT        SEQV
I   1.440      -2.048      -2.246       3.685       3.591
C  0.8078E-05 -0.1237E-01 -0.1309      0.1309      0.1252
O   2.221       1.786      -1.440       3.661       3.464
```

```
             ** MEMBRANE PLUS BENDING **  I=INSIDE C=CENTER O=OUTSIDE
      SX          SY          SZ          SXY         SYZ         SXZ
I  -3.621       60.20       122.9      -5.920       0.000       0.000
C  -1.704       62.44       121.5      -5.920       0.000       0.000
O  0.2132       64.67       120.0      -5.920       0.000       0.000
      S1          S2          S3          SINT        SEQV
I   122.9       60.75      -4.166       127.1       110.1
C   121.5       62.98      -2.246       123.7       107.2
O   120.0       65.21     -0.3260       120.4       104.4

             ** PEAK **  I=INSIDE C=CENTER O=OUTSIDE
      SX          SY          SZ          SXY         SYZ         SXZ
I   0.000       1.041     -0.1982      0.7776       0.000       0.000
C -0.5316E-01 -0.2285     -0.1832     -0.8610E-02   0.000       0.000
O -0.1388E-15  0.3495      0.5196E-01  -1.287       0.000       0.000
      S1          S2          S3          SINT        SEQV
I   1.456     -0.1982     -0.4151       1.872       1.773
C -0.5274E-01 -0.1832     -0.2290      0.1762      0.1584
O   1.474      0.5196E-01  -1.124       2.598       2.254

             ** TOTAL **  I=INSIDE C=CENTER O=OUTSIDE
      SX          SY          SZ          SXY         SYZ         SXZ
I  -3.621       61.25       122.7      -5.143       0.000       0.000
C  -1.757       62.21       121.3      -5.929       0.000       0.000
O  0.2132       65.02       120.1      -7.207       0.000       0.000
      S1          S2          S3          SINT        SEQV        TEMP
I   122.7       61.65      -4.026       126.7       109.8       0.000
C   121.3       62.75      -2.302       123.6       107.1
O   120.1       65.81     -0.5786       120.7       104.7       0.000
```

4.2-Limit-Load Analysis Method

The Non-linear stress analysis techniques are recommended as per API 579-1/ ASME FSS-1 part 4.4.4 Non Linear assessment is best way of estimate of the acceptable load carrying capacity of the component. The assessment procedures for the Limit-Load Analysis Method shall be in accordance with VIII-2, Part 5, paragraph 5.2.3 except that the load case combinations that incorporate the Allowable Remaining Strength Factor as shown in Table 2D.3 may be used in the assessment and RSFa = 0.9

Table 2D.3 – Load Case Combinations and Load Factors for a Limit Load Analysis

Design Conditions		
Criteria	Required Factored Load Combinations	
	Load Case	Load Combination
Global Criteria	1	$\left[1.5\left(P+P_s+D\right)\right]\cdot RSF_a$
	2	$\left[1.3\left(P+P_s+D+T\right)+1.7L+0.54S_s\right]\cdot RSF_a$
	3	$\left[1.3\left(P+P_s+D\right)+1.7S_s+\left(1.1L \text{ or } 0.54W\right)\right]\cdot RSF_a$
	4	$\left[1.3\left(P+P_s+D\right)+1.1W+1.1L+0.54S_s\right]\cdot RSF_a$
	5	$\left[1.3\left(P+P_s+D\right)+1.1E+1.1L+0.21S_s\right]\cdot RSF_a$

STEP 1 – Develop a numerical model of the component including all relevant geometry characteristics. The model used for the analysis shall be selected to accurately represent the component geometry, boundary conditions, and applied loads. The same model was used as in see Figure 1 & 2.

STEP 2 – Define all relevant loads and applicable load cases. The only load to be considered is internal pressure and associated thrust pressure.

1.5 (P+Ps+D) x RSFa = 1.5*(4.35+0+0)*0.9 = 5.872 Mpa and axial trust of nozzle = 27.96 Mpa

STEP 3 – An elastic-perfectly plastic material model with small displacement theory was used in the analysis. The von Mises yield function and associated flow rule was utilized with a yield strength defining the plastic limit shall equal 1.5S.

STEP 4 – Perform a limit-load analysis for each of the load case combinations. **<u>If convergence is achieved,</u>** the component is stable under the applied loads for this load case. Otherwise, the component configuration does not meet the criterion.

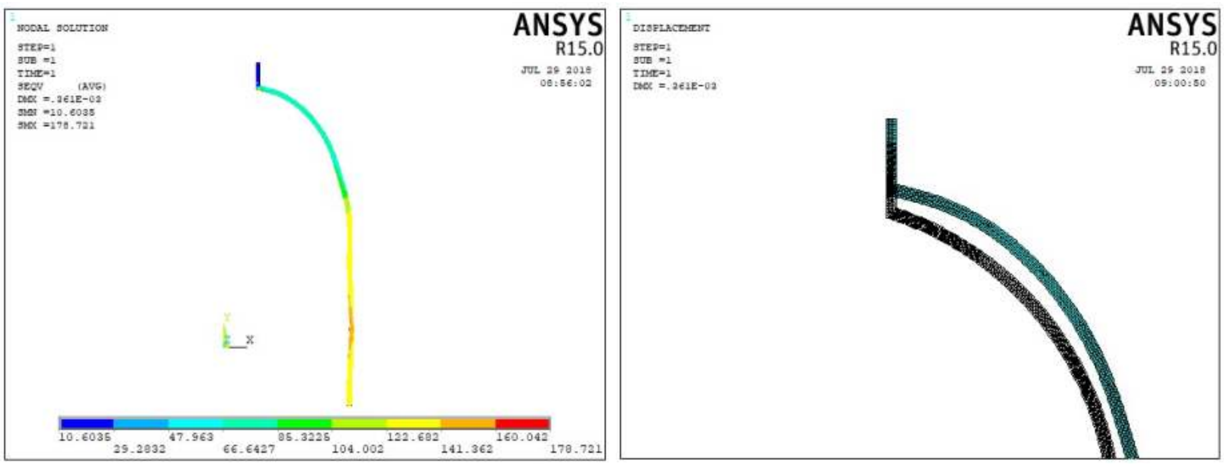

Figure 9&10 - Results of the Limit load Analysis at Factored Load of 5.872 Mpa

S O L U T I O N   O P T I O N S from Ansys APDL

```
PROBLEM DIMENSIONALITY. . . . . . . . . . . . .AXISYMMETRIC
DEGREES OF FREEDOM. . . . . . UX   UY
ANALYSIS TYPE . . . . . . . . . . . . . . . . .STATIC (STEADY-STATE)
PLASTIC MATERIAL PROPERTIES INCLUDED. . . . . .YES
NEWTON-RAPHSON OPTION . . . . . . . . . . . . .PROGRAM CHOSEN
GLOBALLY ASSEMBLED MATRIX . . . . . . . . . . .SYMMETRIC

*** NOTE ***                            CP =      42.516   TIME= 08:54:45
Present time 0 is less than or equal to the previous time.  Time will
default to 1.

*** NOTE ***                            CP =      42.547   TIME= 08:54:45
Results printout suppressed for interactive execute.

*** NOTE ***                            CP =      42.547   TIME= 08:54:45
This nonlinear analysis defaults to using the full Newton-Raphson
solution procedure.  This can be modified using the NROPT command.

SOLCONTROL,ON uses sparse matrix direct solver

*** NOTE ***                            CP =      42.562   TIME= 08:54:45
```

```
 The conditions for direct assembly have been met.  No .emat or .erot
 files will be produced.

 *** WARNING ***                         CP =      42.562   TIME= 08:54:45
 The program chosen initial timestep/load-factor is arbitrary.  It is necessary for the user to
supply a suitable initial
 timestep/load-factor through the NSUB or DELTIM command for   convergence and overall efficiency.

                      L O A D   S T E P   O P T I O N S

LOAD STEP NUMBER. . . . . . . . . . . . . . . .     1
TIME AT END OF THE LOAD STEP. . . . . . . . . .  1.0000
AUTOMATIC TIME STEPPING . . . . . . . . . . . .    ON
INITIAL NUMBER OF SUBSTEPS . . . . . . . . .     1
MAXIMUM NUMBER OF SUBSTEPS . . . . . . . . .  1000
MINIMUM NUMBER OF SUBSTEPS . . . . . . . . .     1
START WITH TIME STEP FROM PREVIOUS SUBSTEP.   YES
MAXIMUM NUMBER OF EQUILIBRIUM ITERATIONS. . . .    15
STEP CHANGE BOUNDARY CONDITIONS . . . . . . . .    NO
TERMINATE ANALYSIS IF NOT CONVERGED . . . . . .YES (EXIT)
CONVERGENCE CONTROLS . . . . . . . . . . . . . .USE DEFAULTS
COPY INTEGRATION POINT VALUES TO NODE . . . . .YES, FOR ELEMENTS WITH

ACTIVE MAT. NONLINEARITIES
PRINT OUTPUT CONTROLS . . . . . . . . . . . . .NO PRINTOUT
DATABASE OUTPUT CONTROLS . . . . . . . . . . . .ALL DATA WRITTEN
                                                  FOR THE LAST SUBSTEP


DISP CONVERGENCE VALUE   = 0.1511E-01  CRITERION= 0.1792E-04
EQUIL ITER   1 COMPLETED.  NEW TRIANG MATRIX.  MAX DOF INC=  0.3584E-03
FORCE CONVERGENCE VALUE  = 0.4575E-08  CRITERION= 0.1295E-01 <<< CONVERGED
curEqn=   5606  totEqn=   5605 Job CP sec=     44.547
Factor Done= 100% Factor Wall sec=      0.006 rate=     514.2 Mflops
DISP CONVERGENCE VALUE   = 0.1449E-10  CRITERION= 0.1792E-04 <<< CONVERGED
EQUIL ITER   2 COMPLETED.  NEW TRIANG MATRIX.  MAX DOF INC =  0.3769E-12
    >>> SOLUTION CONVERGED AFTER EQUILIBRIUM ITERATION   2
```

Step 5 .The results of the analysis are shown in above, **convergence was achieved** at the factored load condition; therefore the vessel passes limit load analysis for this load case.

4.3- Elastic-Plastic Analysis

The Non-linear stress analysis techniques are recommended as per API 579-1/ ASME FSS-1 part 4.4.4 Non Linear assessment is best way of estimate of the acceptable load carrying capacity of the component. The assessment procedures for Elastic-Plastic Analysis shall be in accordance with VIII-2, Part 5, paragraph 5.2.4 except that the load case combinations that incorporate the Allowable Remaining Strength Factor as shown in Table 2D.5 may be used in the assessment and RSFa = 0.9

Table 2D.5 – Values of β for an FFS Assessment Based on Elastic-Plastic Analysis

Construction Code	β
PD 5500	$2.35 \cdot RSF_a$ (1)
EN 13345	$2.4 \cdot RSF_a$ (1)
ASME Section VIII, Division 2, 2007 Edition and later	$2.4 \cdot RSF_a$ (1)
ASME Section VIII, Division 2, prior to the 2007 Edition	$3.0 \cdot RSF_a$ (1)
ASME Section VIII, Division 1, 1999 Edition and later	$3.5 \cdot RSF_a$ (1)
ASME Section VIII, Division 1, prior to the 1999 Edition	$4.0 \cdot RSF_a$ (1)

STEP 1 – Develop a numerical model of the component including all relevant geometry characteristics. The model used for the analysis shall be selected to accurately represent the component geometry, boundary conditions, and applied loads. The same model was used as in see Figure 1 & 2.

STEP 2 – Define all relevant loads and applicable load cases. The only load to be considered is internal pressure and associated thrust pressure.

2.4 (P) x RSFa = 2.4*(4.35)*0.9 = 9.39 Mpa and axial trust on nozzle = 44.74 Mpa

STEP 3 – An elastic-perfectly plastic model was utilized and von Mises yield function and associated flow rule was utilized. The effects of non-linear geometry are considered in the analysis.

STEP 4- Perform an elastic-plastic analysis. **<u>If convergence is achieved</u>**, the component is stable under the applied loads for this load case. Otherwise, the component configuration does not meet the criterion or

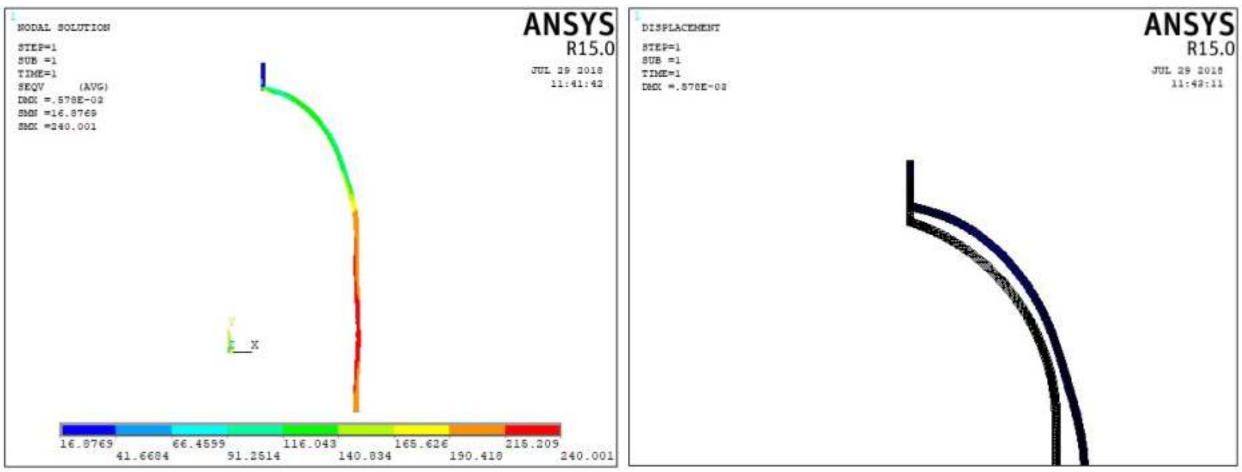

Figure 11&12 - Results of the Limit load Analysis at Factored Load of 9.39 Mpa

```
   S O L U T I O N   O P T I O N S

PROBLEM DIMENSIONALITY. . . . . . . . . . . . .AXISYMMETRIC
DEGREES OF FREEDOM. . . . . . UX   UY
ANALYSIS TYPE . . . . . . . . . . . . . . . . .STATIC (STEADY-STATE)
PLASTIC MATERIAL PROPERTIES INCLUDED. . . . . .YES
NEWTON-RAPHSON OPTION . . . . . . . . . . . . .PROGRAM CHOSEN
GLOBALLY ASSEMBLED MATRIX . . . . . . . . . . .SYMMETRIC

*** NOTE ***                            CP =      86.656   TIME= 11:17:34
Present time 0 is less than or equal to the previous time.  Time will
default to 1.

*** NOTE ***                            CP =      86.656   TIME= 11:17:34
Results printout suppressed for interactive execute.

*** NOTE ***                            CP =      86.656   TIME= 11:17:34
This nonlinear analysis defaults to using the full Newton-Raphson
solution procedure.  This can be modified using the NROPT command.

SOLCONTROL,ON uses sparse matrix direct solver

*** NOTE ***                            CP =      86.703   TIME= 11:17:34
```

```
 The conditions for direct assembly have been met.  No .emat or .erot
 files will be produced.

 *** WARNING ***                         CP =      86.703   TIME= 11:17:35
 The program chosen initial timestep/load-factor is arbitrary.  It is  necessary for the user to
supply a suitable initial  timestep/load-factor through the NSUB or DELTIM command for
convergence and overall efficiency.


L O A D   S T E P   O P T I O N S

   LOAD STEP NUMBER. . . . . . . . . . . . . . . .     1
   TIME AT END OF THE LOAD STEP. . . . . . . . . .  1.0000
   AUTOMATIC TIME STEPPING . . . . . . . . . . . .    ON
      INITIAL NUMBER OF SUBSTEPS . . . . . . . . .     1
      MAXIMUM NUMBER OF SUBSTEPS . . . . . . . . .  1000
      MINIMUM NUMBER OF SUBSTEPS . . . . . . . . .     1
      START WITH TIME STEP FROM PREVIOUS SUBSTEP .   YES
   MAXIMUM NUMBER OF EQUILIBRIUM ITERATIONS. . . .    15
   STEP CHANGE BOUNDARY CONDITIONS . . . . . . . .    NO
   TERMINATE ANALYSIS IF NOT CONVERGED . . . . . .YES (EXIT)
   CONVERGENCE CONTROLS. . . . . . . . . . . . . .USE DEFAULTS
   COPY INTEGRATION POINT VALUES TO NODE . . . . .YES, FOR ELEMENTS WITH
                                                  ACTIVE MAT. NONLINEARITIES
   PRINT OUTPUT CONTROLS . . . . . . . . . . . . .NO PRINTOUT
   DATABASE OUTPUT CONTROLS. . . . . . . . . . . .ALL DATA WRITTEN   FOR THE LAST SUBSTEP


  SOLUTION MONITORING INFO IS WRITTEN TO FILE= file.mntr

 DISP CONVERGENCE VALUE   = 0.2416E-01  CRITERION= 0.2866E-04
 EQUIL ITER   1 COMPLETED.  NEW TRIANG MATRIX.  MAX DOF INC=  0.5732E-03
 FORCE CONVERGENCE VALUE  = 0.2847      CRITERION= 0.2070E-01
 curEqn=   5606  totEqn=   5605 Job CP sec=     89.266
 Factor Done= 100% Factor Wall sec=      0.008 rate=     382.4 Mflops
 DISP CONVERGENCE VALUE   = 0.1777E-04  CRITERION= 0.2870E-04 <<< CONVERGED
 EQUIL ITER   2 COMPLETED.  NEW TRIANG MATRIX.  MAX DOF INC=  0.9573E-06
 FORCE CONVERGENCE VALUE  = 0.4785E-02  CRITERION= 0.2113E-01 <<< CONVERGED
 >>> SOLUTION CONVERGED AFTER EQUILIBRIUM ITERATION   2
```

Step 5 .The results of the analysis are shown in above, **convergence was achieved** at the factored load condition; therefore the vessel passes Elastic-Plastic Analysis for this load case.

5.0 Concluding Remarks

Level 1 assessment = Failed to meet criterion
Level 2 assessment = Failed to meet criterion
Level 3 assessment (Finite Element Analysis)
1. Elastic Stress Analysis and Local Failure = ***Pass***
2. Limit load Analysis = ***Pass***
3. Elastic–Plastic Analysis = ***Pass***

The alternative methods of Limit load analysis and Elastic–Plastic analysis are used to verify the results obtained from elastic stress analysis, thus the shell with corroded portion found much safer for its continual operation. The vessel is exempted from Re-rate, Repair and Retirement.

References

ANSYS (version 15.0) [Computer software]
ASME Boiler & Pressure Vessel Code, Section VIII Div.2, part 5 Ed 2017
Dennis R. Moss, Pressure Vessel Design Manual Ed 4
Fitness-For-Service API 579-1/ASME FFS-1, Ed 2016
Fitness-For-Service Manual API 579-2/ASME FFS-2 2009
ASME Section II Part D Edition 2017.