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## PREDICTION OF FRACTURE STRESSES OF HIGH PRESSURE GAS CYLINDERS CONTAINING CRACK LIKE FLAWS USING VARIOUS METHODS

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### ABSTRACT

Full scale tests were conducted on high pressure gas cylinders containing crack like flaws. The cylinders were then pressurized to destruction and the membrane stress at failure in the cylinder wall was calculated from the failure pressure. Mechanical properties including tensile and fracture data were obtained on specimens representing the heats of the tested cylinders. Analyses were performed to predict the failure stresses using several methods available in the open literature. This paper presents the results of the predicted and measured fracture stresses.

### 1.0 INTRODUCTION

Considerable progress has been made in the development of standards for fitness-for-service applications. Two examples of such standards are API 579 [1] and BS 7910[2]. Both these standards provide methods to assess the components containing cracks and local thin areas (LTA).

Full scale fracture tests were conducted on high pressure (4500 psi) gas cylinders in 1988 [3]. A subset of the data obtained from the tested cylinders have been used in this paper to predict the fracture stresses using various fracture mechanics based methods available in the open literature. The methods used to predict the failure stress level include: API 579[1], BS 7910[2] and Battelle [4]. The results of these analyses indicated the LEFM based FAD approach predicted much lower fracture stress compared to those measured. The Battelle's ,API 579 Level 1 LTA and modified LEFM methods predicted the fracture stresses higher than those by BS7910, but lower than those measured stresses. In summary, all the above listed methods predictability is not very accurate, but it is on the conservative side.

### 2.0 NOMENCLATURE

a = surface crack depth
l = surface crack length
d = cylinder inside diameter
D = cylinder outside diameter
$t_s$ = thickness at machined flaw
$K_{IC}(J)$ = plane-strain fracture toughness obtained from J tests using ASTM E-813 test method
Kc = plane stress fracture toughness
J = elastic plastic fracture parameter
J-R= J vs. Δa curve obtained
LTA= local thin area
LEFM= linear elastic fracture mechanics
$\sigma_U$ =UTS = ultimate tensile strength
$\sigma_Y$ =YS = yield strength
$\sigma_P$ = predicted fracture stress,
$\sigma_f$ = measured fracture stress
$\sigma_{flow}$ = flow strength = 0.5x (UTS + YS)
$M_t$ = stress intensity magnification factor for a thru wall crack
$M_p$ = stress intensity magnification factor for a part thru wall crack

## 3.0 TEST DATA

Several identical cylinders containing crack like flaws were tested to failure. The resulted of these tests were documented in reference [3]. The cylinders were manufactured from two heats of patented 4134V steel, having an ultimate tensile strength of 155 to 175 ksi. The fracture toughness $K_{IC}(J)$ exceeded 85 ksi $in^{1/2}$ as required to meet the DOT cylinder fabrication requirements. The fracture toughness data was determined from test performed on compact tension specimens. The testing was performed the ASTM E 813. All the tested specimens met the validity requirements for remaining ligament size. Sharp crack like flaws of varying dimensions were machined on the exterior of the cylinder using an electro discharge machining (EDM) process. The flaws were machined to a semi elliptical geometry with a width of 0.006 inches and tip radius of 0.003 inches. The flawed cylinders were pressurized to fracture at room temperature. The resultant fracture hoop stresses ($\sigma_f$) were calculated using the mean diameter and thin wall pressure vessel theory (PD/2t). Table 1 shows the results of the tests for 4 of the cylinders for the same heat of steel. The geometry of both the initial flaw and the cylinder are provided in Table 1. Accurate dimensions of the initial flaw size were measured following the tests. All tested cylinders bulged at the flaw and burst exhibited a ductile fracture mode. Figure 1 shows a photograph of a tested cylinder. Table 2 provides the tensile and fracture data of the cylinders evaluated in this paper.

The fracture toughness $K_{IC}(J)$ of the tested cylinder is large enough, so that fracture state of the cylinder meets the criterion for plane stress as defined by "t" < $2.5(K_{IC}(J)/\sigma_Y)^2$. Plane Stress fracture toughness values were calculated using the methodology proposed by Irwin [5]. Using the following correction to $K_{IC}(J)$.

$$K_c = K_{IC}(J)\ (1 + 1.4(\beta_{Ic})^2)^{0.5} \quad (1)$$

$$\beta_{Ic} = (1/t)\ [(K_{IC}(J)/\sigma_Y]^2 \quad (2)$$

Above Equation 13 is only valid for the maximum value of $\beta_{Ic}$ of 1.0. Thus in Equation 1, the value of $\beta_{Ic}$ used was lesser of 1.0 or that given by Equation 2. The values are provided in Table 2

**Table 1 of Geometry and Test Results**

| Cylinder No. | D in | t in | l in | a in | $\sigma_f$ ksi |
|---|---|---|---|---|---|
| 1 | 9.32 | 0.290 | 2.0 | 0.182 | 125.6 |
| 2 | 9.32 | 0.295 | 2.0 | 0.205 | 112.1 |
| 3 | 9.33 | 0.300 | 2.0 | 0.225 | 117.0 |
| 4 | 9.30 | 0.295 | 2.75 | 0.206 | 103.9 |
| 5 | 9.31 | 0.291 | 2.0 | 0.222 | 111.6 |
| 6 | 9.32 | 0.285 | 2.75 | 0.227 | 91.3 |

Note: Cylinders 1-4 were from heat number HP 17 of reference [3]
Cylinders 5-6 were from heat number HP 19 of reference [3]

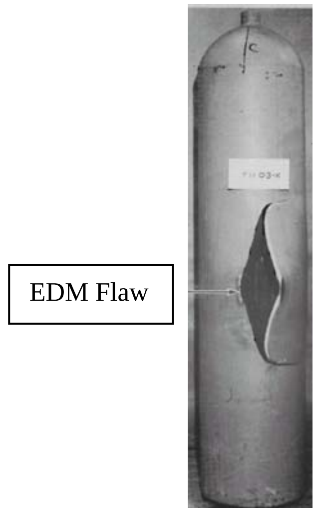



**Figure 1 Photograph of tested cylinder Number 3**

**Table 2 Tensile and Fracture Data Heats**

| HEAT NO. | $\sigma_U$ | $\sigma_Y$ | $J_{Ic}$ | $K_{Ic}(J)$ | $K_c$ |
|---|---|---|---|---|---|
| | KSI | KSI | IN-LB/IN^2 | KSI IN^0.5 | |
| HP17 | 173 | 160 | 513 | 124 | 192 |
| HP17 | 173 | 160 | 480 | 120 | 186 |
| HP17 | 168 | 155 | 529 | 126 | 195 |
| HP17 | 168 | 155 | 555 | 129 | 200 |
| HP17 | 168 | 155 | 529 | 126 | 195 |
| HP17 | 168 | 154 | 563 | 130 | 201 |
| HP17 | 174 | 161 | 418 | 112 | 173 |
| HP17 | 174 | 161 | 396 | **109** | **168** |
| HP17 | 171 | 160 | 822 | 157 | 243 |
| HP17 | 174 | 163 | 663 | 141 | 218 |
| HP17 | 174 | 163 | 626 | 137 | 212 |
| **Average** | **171** | **159** | **538** | **127** | **198** |
| **STDev** | **3** | **3** | **119** | **13** | **21** |
| HP19 | 168 | 154 | 411 | 111 | 172 |
| HP19 | 172 | 160 | 247 | **86** | **133** |
| HP19 | 168 | 160 | 529 | 126 | 195 |
| HP19 | 160 | 148 | 301 | 95 | 147 |
| HP19 | 160 | 148 | 307 | 96 | 149 |
| HP19 | 162 | 148 | 327 | 99 | 153 |
| **Average** | **165** | **153** | **354** | **102** | **158** |
| **STDev** | **5** | **6** | **101** | **14** | **22** |

**Note: Heat HP-17** CVN (avg) =20 ft-lb, @RT,TL, 10 X 5 mm specimens
**Heat HP-19** CVN (avg) =16 ft-lb, @RT,TL, 10 X 5 mm specimens

The J-R data from the ASTM E 813.testing was fit to the following equations. These equations were fit to the minimum J-R Data

Heat HP=17 $J = 1520.2(\Delta a)^{0.2718}$ (3)

Heat HP=19 $J = 1081.1(\Delta a)^{0.265}$ (4)

## 4.0 FRACTURE STRESS PREDICTION METHODS AND RESULTS

The following listed methods were used in the analyses. Brief description and parameters used in each method are presented in the following sections. Except as noted the average material tensile properties are used with the minimum fracture toughness values from Table 2 to make the comparisons between methods.

4.1 Battelle Method [4]
4.2 API 579 Local Thin Area Level 1
4.3 API 579 and BS 7910 Crack Like Flaws Level 2
4.4 BS7910 Crack Like Flaws Level 3

### 4.1 Battelle Method

Kiefner et al in the 1972 [4] developed models for flow-stress controlled and fracture depended conditions to predict the failure stress for surface flawed line pipe. The following equations for the fracture dependent case were taken from [4] to predict the fracture stresses of the tested cylinders.

$$\left[\frac{\dfrac{12C_v}{A_c E\pi}}{8c_{eq}\sigma_f^2}\right] = \ln \sec \frac{\pi}{2}\left[\frac{M_p\sigma_p}{\sigma_f}\right] \qquad (5)$$

Where:

Cv = CVN energy in ft-lb
Ac = CVN specimen fracture area, in^2
E = Modulus of elasticity, psi
2Ceq = Equivalent length of flaw = A/a, in.
A = flaw area, for semi elliptical flaw = Π x l x a/2
2Ceq = Π x l /2 , in.
Mp = (1-a/tMt)/(1-a/t)
Mt = [1 + (1.255 Ceq^2/0.5dt) – 0.0135Ceq^4/(0.5dt)^2]^0.5

The failure stress using this method are calculated using this method are calculated by substituting the required parameters into equations (5) The predicted fracture stress values for each cylinder is presented in Table 4.

**Table 4 Predicted Fracture Stress Battelle Method**

| Cylinder Number | Measured $\sigma_f$ ksi | Predicted $\sigma_p$ ksi | Ratio $\sigma_f/\sigma_p$ |
|---|---|---|---|
| 1 | 125.6 | 113.8 | 1.1 |
| 2 | 112.1 | 104.7 | 1.07 |
| 3 | 117.0 | 95.6 | 1.22 |
| 4 | 103.9 | 75.9 | 1.36 |
| 5 | 111.6 | 82.5 | 1.35 |
| 6 | 91.3 | 52.5 | 1.73 |

### 4.2 API 579 LTA Level 1 Method

In this approach, the API 579, Level 1 procedure to assess a local thin area (LTA) in Section 5 is used. The following Equation 6 (Equation 5.11 in API 579) is the fundamental equation to calculate the Residual Strength Factor (RSF) in the presence of an LTA. The flaws in the tested cylinders have been assumed to be LTAs. The RSF is defined as the ratio of the cylinder's burst strength with a flaw ($\sigma_p$ ) divided by the cylinder's burst strength without a flaw($\sigma_{flow}$). To apply this method to the cylinders it is assumed that cylinder's burst strength is controlled by the material flow strength and the RSF is defined as ratio of $\sigma_f / \sigma_{flow.}$ The API LTA level 1 method as defined below if the same as the flow stress dependent material model to evaluate surface flaws developed by Kiefner et al in the 1972 [4] The API LTA level 1 method uses different folias factor than the Kiefner method.

$$\frac{\sigma_p}{\sigma_f} = \frac{1-\dfrac{a}{t}}{1-\dfrac{1}{M_t}\dfrac{a}{t}} \qquad (6)$$

Where:

$$M_t = (1 + 0.48\lambda^2)^{1/2}$$
$$\lambda = 1.285(l) / (d \times t)^{1/2}$$

Using the above equations, the values of the predicted fracture stresses for the six cylinders are presented in Table 5.

**Table 5 Predicted Fracture Stress API 579 LTA Level 1**

| Cylinder Number | Measured $\sigma_f$ ksi | Predicted $\sigma_p$ ksi | Ratio $\sigma_f/\sigma_p$ |
|---|---|---|---|
| 1 | 125.6 | 105.4 | 1.19 |
| 2 | 112.1 | 94.0 | 1.19 |
| 3 | 117.0 | 83.3 | 1.4 |
| 4 | 103.9 | 79.9 | 1.29 |
| 5 | 111.6 | 74.8 | 1.5 |
| 6 | 91.3 | 55.4 | 1.64 |

### 4.3 Failure Assessment Diagrams

The use of the failure assessment diagram (FAD) has become the standard method to evaluate crack like flaws found in components post construction for fitness for service. The FAD provides a methodology to evaluate the interaction between a pure fracture mechanics approach and a pure limit load failure. The limit load condition in the FAD approach addresses the condition flow-stress controlled failure of a component. Both the API 579 an BS 7910 Standards have adopted the FAD methodology for the evaluation of crack like flaws. The failure criterion for both standards is given by equation (7) and illustrated in Figure 2 for the Cylinder 3.

$$K_r = (1 - 0.14L_r^2) [(0.3 + 0.7\exp(-0.65L_r^6)] \qquad (7)$$

Where:

$$K_r = K_{I\ APPLIED} / K_{MATERIAL} \qquad (8)$$

$$L_r = \sigma_{Reference} / \sigma_{Yield} \qquad (9)$$

For all practical purpose, the API 579 Level 2 procedure is identical to that of BS 7910 Level 2. The two standards differ in there solution for $K_{Applied}$ and $\sigma_{Reference.}$ These difference are shown in the data provided below.

Two sets of material properties Kmat were used in the analysis. One is plane strain fracture toughness $K_{IC}(J)$ obtained from J-Integral tests and the other is the plane stress fracture toughness $K_{c.}$ obtained using the Irwin's [ 5]. The numerical values are provided in Table 2

The membrane stress Pm from the analysis using API 579 and BS7910 is equal to the predicted fracture hoop stress $\sigma_p$ because all safety factors are set equal to one. The analyzed cylinders were of seamless construction, thus the required residual stresses were input as zero. The curvature effect was included in the analyses. Table 7 shows the results of the analyses the API 579 Level 2 analysis and Table 8 shows the result for the BS 7910 analysis.

**Figure 2 FAD for cylinder number 3 with $K_{mat} = K_{Ic}(J)$**

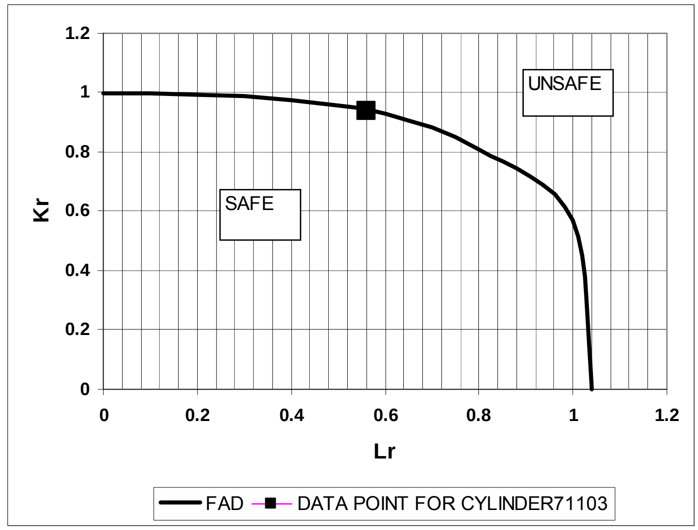



**Table 7 Predicted Fracture Stress API 579 Level 2**

| Cylinder Number | Measured $\sigma_f$ ksi | Predicted $K_{IC}(J)$ $\sigma_p$ ksi | Ratio $\sigma_f/\sigma_p$ | Predicted $K_c$ $\sigma_p$ ksi | Ratio $\sigma_f/\sigma_p$ |
|---|---|---|---|---|---|
| 1 | 125.6 | 68 | 1.6 | 91 | 1.4 |
| 2 | 112.1 | 63 | 1.8 | 86 | 1.3 |
| 3 | 117.0 | 61 | 1.9 | 83 | 1.4 |
| 4 | 103.9 | 53 | 1.96 | 74 | 1.4 |
| 5 | 111.6 | 48 | 2.3 | 70 | 1.6 |
| 6 | 91.3 | 38 | 2.4 | 55 | 1.6 |

**Table 8 Predicted Fracture Stress BS 7910 Level 2**

| Cylinder Number | Measured $\sigma_f$ ksi | Predicted $K_{IC}(J)$ $\sigma_p$ ksi | Ratio $\sigma_f/\sigma_p$ | Predicted $K_c$ $\sigma_p$ ksi | Ratio $\sigma_f/\sigma_p$ |
|---|---|---|---|---|---|
| 1 | 125.6 | 51.9 | 2.4 | 68.9 | 1.8 |
| 2 | 112.1 | 43.6 | 2.6 | 59.1 | 1.9 |
| 3 | 117.0 | 37.0 | 3.2 | 50.9 | 2.3 |
| 4 | 103.9 | 32.7 | 3.2 | 46.0 | 2.3 |
| 5 | 111.6 | 28.3 | 3.9 | 41.1 | 2.7 |
| 6 | 91.3 | 17.7 | 5.1 | 26.4 | 3.5 |

An additional comparison between the failure data and the API 579 Level 2 FAD analysis is shown below in Table 9 The average value for the plane stress fracture toughness is used in the Table 9 comparison. The average tensile properties are use as in the previous data.

**Table 9 Predicted Fracture Stress API 579 Level 2**

| Cylinder Number | Measured $\sigma_f$ ksi | Predicted $K_{IC}(J)$ $\sigma_p$ ksi | Ratio $\sigma_f/\sigma_p$ |
|---|---|---|---|
| 1 | 125.6 | 99 | 1.2 |
| 2 | 112.1 | 94 | 1.2 |
| 3 | 117.0 | 91 | 1.3 |
| 4 | 103.9 | 81 | 1.3 |
| 5 | 111.6 | 78 | 1.4 |
| 6 | 91.3 | 63 | 1.4 |

### 4.4 BS7910 Level 3 Ductile Tearing

In this method, generalized Level 2FAD Equation 7 was used in the analysis. The J-R data from equations 4 and 5 were applied for the heats corresponding to the cylinder to perform a ductile tearing analysis. The specified minimum and maximum ductile tearing was 0.001 in. and 0.05 in. Figure 3 shows a FAD for cylinder 1. The contour of the calculated Kr and Lr touches the FAD curve, then that point is the critical fracture point, from which the fracture stress is calculated. Table 10 shows the results of these calculations. Table 10 also shows the results of Level 2 analysis with $K_{mat}$ = $K_{Ic}(J)$. The stresses calculated by Level 2 and Level 3 are almost equal, since the value of $K_{Ic}(J)$ were obtained from the same J-R curves at 0.2mm crack growth.

**Figure 3 Level 3 FAD Ductile Tearing Cylinder 1**

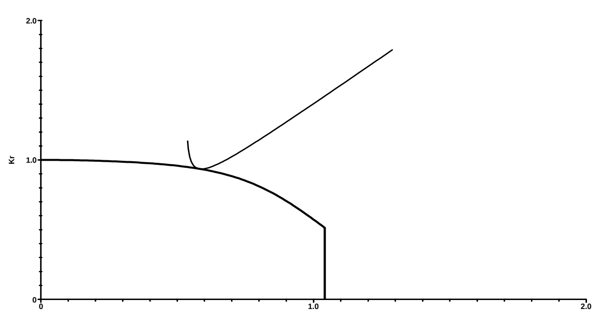


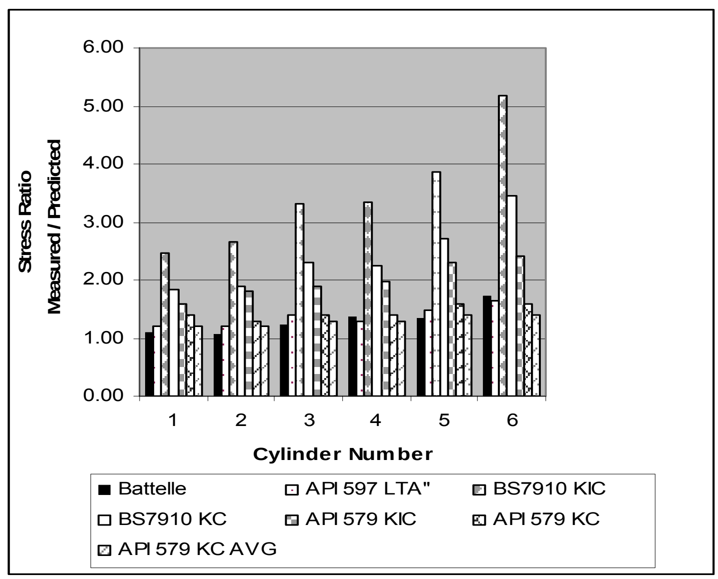

**Table 10 Predicted Fracture Stress BS 7910 Level 3**

| Cylinder Number | Measured $\sigma_f$ ksi | Predicted, $K_{IC}(J)$ $\sigma_p$ ksi | Predicted J-R data $\sigma_p$ ksi | Ratio $\sigma_f/\sigma_p$ |
|---|---|---|---|---|
| 1 | 125.6 | 51.9 | 50.8 | 2.5 |
| 2 | 112.1 | 43.6 | 42.2 | 2.6 |
| 3 | 117.0 | 37.0 | 35.3 | 3.3 |
| 4 | 103.9 | 32.7 | 31.2 | 3.3 |
| 5 | 111.6 | 28.3 | 28.9 | 3.8 |
| 6 | 91.3 | 17.7 | 17.6 | 5.1 |

### 5.0 RESULTS AND DISCUSSION

The results obtained by all above described methods are summarized iin Figure 4.

**Figure 4 Comparison of results**




A review of data provided in Figure 4 shows that all the methods predicted a fracture stress less than that measured for the respective cylinder by test. The most conservative predictions were those obtained in the BS 7910 Level 2 FAD analysis.

The FAD approach has two most important parameters. One is the fracture toughness Kmat and the second is the stress intensity effect at the flaw. Since the tested cylinders are in the plane stress fracture state, the use of plane -strain fracture property such as $K_{IC}$(J) results in a highly conservative prediction. When the plane stress fracture toughness (KC) is used, the result is a relatively less conservative prediction compared to that failure stress calculated using plane strain conditions.

The API 579 FAD method differs from the BS 7910 approach in that the solution for the stress intensity. The stress intensity solution in BS 7910 is based on curve plate equation and is increased by a magnification factor M (Folias Factor) to address bulging. The in API 579 addresses the bulging effect directly in the stress intensity solution. Both method use a flat plat solution amplified by a folias factor for the reference stress of limit load solution. The fundamental equation to calculate the basic magnification factor (M) due to the bulging effect is similar in API 579, Bettelle and BS 7910. However, in BS 7910, the bulging factor is further increased by 1.2 in the reference stress solution. This further reduces the predicted fracture stress in the BS7910 method.

The API 579 Level 1 LTA method is presented in the standard as being most applicable to local thin areas. The fracture criterion of this method is that when the nominal stress multiplied by the bulging factor M becomes equal to the material's flow strength, fracture occurs. This model is known as flow strength controlled model and it is independent of fracture toughness. As shown in Table 5, the predictability of fracture stresses is fairly good with exception of the two cylinders with relatively deep flaws. Kiefner el al applies this method to crack like in reference 4. The method provides good results for limit load controlled cases.

The Battelle fracture method was show to produce good agreement with test on line pipe in reference 4. The results shown in Table 4 are similar those in the Battelle work.. This is not surprising, since in the Bettelle's method, for high toughness material, the effect of toughness becomes negligible and only flow strength controls the fracture stress, which is the same criterion as in API 579 Level 1 LTA method.

These FAD approach will result in a conservative prediction unless proper fracture toughness (Kmat) is applied. It also appears that if the material's $K_{Ic}$ is high enough, so that the cylinder wall is in the plane- stress fracture state, then the fracture prediction by flow strength controlled models such API 579 Level 1 LTA model would result in less conservative results.

It is recognized that most of the API579 and BS7910 fracture mechanics methods are used in determining the fitness- for – service of an existing structure in the presence of flaws, thus a conservative approach is justified.

## 6.0 CONCLUSIONS

From the results of the analysis performed on flawed cylinders, the following conclusions can be drawn.

(1) For relatively high toughness, plane- stress fracture state condition, the FAD approach provided in BS7910 and API 579 Level 2 results in much lower predicted fracture stress compared that measured by test.

(2) For relatively high toughness, plane stress fracture state condition, Battelle's and API 579 local thin area approach provides a relatively better prediction of fracture stresses, even though these predicted stresses are lower than those measured stresses.

## ACKNOWLEDGMENTS

Put acknowledgments here.

## REFERENCES

[1] API 579, "Recommended Practice for Fitness–for–Service", American Petroleum Institute, Washington D.C., First Edition 2000

[2] BS7910:1999, "Guide on methods for assessing the acceptability of flaws in metallic structures", BSI, London, W1A 2BS

[3]Rana M.D., Selines R.J., "Structural integrity assurance of high-strength steel gas cylinders using fracture mechanics", Engineering Fracture Mechanics, Vol 30, no 6, pp 877-894, 1988, UK

[4] Kiefner, J.F.,Maxey, W.A., Eiber, R.J., Duffy, A.R., "Failure stress levels of flaws in pressurized cylinders", Progress in Flaw Growth and Fracture Toughness Testing, ASTM STP 536, American Society of Testing and Materials, 1973, pp.461-481.

[5]Irwin,G.R.,Kraft,J.M.,Paris,P.C.,Wells,A.A.,1987, "Basic Aspects of Crack Growth and Fracture" Naval Laboratory Report 6598, NTIS Number 663882, U.S. Department of Commerce, Springfield, Va., PP 38, 50-53.