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Reliability Computation of Bursting Strength of Ammonia Pipelines Based on Choi's Criterion

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ABSTRACT: The aim of the present work was to predict the bursting pressure of ammonia pipelines using Choi's criterion. The failure of the pipes was evaluated based on the Tresca, von Mises criteria and Weibull criteria. The significance of crack dimensions was recognized using Taguchi techniques. The highly influencing crack dimensions were pipe thickness, crack depth and grade of steel. The results obtained by the Choi's criterion have been validated with in line with those of experimentation, ASME B31G, modified ASME B31G, DNV-RP-F101, SHELL-9, RSTRENG, PCORRC, LG-18 and Fitnet FSS.

KEYWORDS: Ammonia, steel, crack depth, crack length, bursting pressure, Choi's criterion, Tresca criterion, von Mises criterion.

I. INTRODUCTION

Highly toxic ammonia is the most dangerous substance to be transported through long-distance pipelines. Sulfur sticks are burnt to detect small leaks in industrial ammonia refrigeration systems. Larger quantities can be detected by warming the salts with a caustic alkali or with quicklime, when the characteristic smell of ammonia will be at once apparent. Ammonia is an irritant and irritation increases with concentration. Gaseous ammonia affects the mucous membranes and the respiratory tract and severely irritates the eyes. Inhaling high concentrations may cause pulmonary oedema. High gas concentrations in the air may also cause blisters and chemical burns on the skin as revealed in [1]. The Kingman pipeline (Kansas) incident in 2004 is shown in Fig. 1. Reports quote 200 000 gallons of liquid ammonia loss as stated in [2].

Fig. 1. Large plume of escaping ammonia from the Kingman pipeline incident.

A total of 54 female workers fell unconscious and were hospitalized after an ammonia gas pipeline leak in a fishing factory in the Indian state of Tamil Nadu (Jul 5, 2014) as shown in Fig. 2. Seven persons died of asphyxiation after they got trapped inside a cold storage factory following the leakage of ammonia gas at Ranasan GIDC in Vijapur taluka of

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North Gujarat on September 07, 2013 20:48 IST (Press Trust of India). Prima facie it appeared that rupture in a pipeline carrying the gas to the factory resulted into the leakage. A major gas leakage continues 15 days after it started from an Oil India Ltd (OIL) well at Dandewala area in Jaisalmer (Press Trust of India, Sunday October 18, 2015) as shown in Fig. 3.

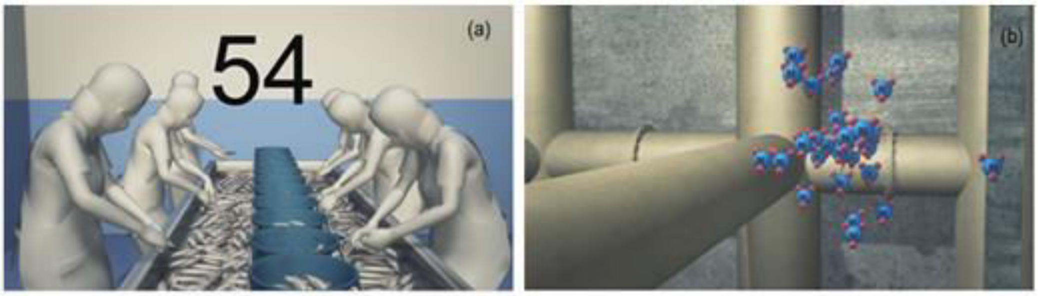

Fig. 2. Ammonia gas leakage in Tamilnadu, India: (a) 54 female workers felt unconscious (b) pipe leakage.

Fig.3. A major gas leakage at Dandewala area, India.

With respect to integrity and safety of a pipe system, it is necessary to know the maximum pressure load it can withstand without leakage and catastrophic fracture. One of the most serious problems of pipes is corrosion. The gas pipes burst due to internal or external corrosion cracks. Minnesota Rules, Part 1513.0160 [3] requires that system piping (piping, fittings, flanges, other components) must be made of steel or other material suitable for anhydrous ammonia service, and must be designed for a pressure not less than the maximum pressure to which they may be subjected in service. System piping components made of, or in part of, brass, copper, zinc, galvanized steel, or cast iron may NOT be used for ammonia service.

Although literature on fracture mechanics of the pipelines is abundant, there is no assessment method that is precise and largely acknowledged. Most popular failure pressure methods for pressurized pipes with active corrosion defects are ASME B31G [4, 5] and modified ASME B31G [6], DNV-RP-F101 [7, 8], SHELL-92 [9, 10], RSTRENG [11, 12], PCORRC [13, 14], LG-18 [15, 16] and Fitnet FSS [17, 18]. Finite element methods have been applied to predict total deformation, von Misess stress, stress intensity factors and J-integral for the applied pressure on the pipes as applied in [19-22].

The present work was motivated to optimize safety criteria for ASTM 106 grade A, ASTM 106 grade B and ASTM 106 grade C steel pipes (seamless) of 100 mm diameter 5000 mm length. The present study was to predict the bursting pressure of the pipes with different crack dimensions using Cochy criterion. In [23], the bursting pressure was optimized using Taguchi techniques. The results were also cross-checked with those computed from ASME B31G, modified ASME B31G, DNV-RP-F101, SHELL-92, PCORRC, LG-18, RSTRENG and Fitnet FSS criteria. The

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Weibull criterion was also applied to find the reliability of failure. The results were also verified using finite element analysis with respect to von Mises stress and stress ratio (von Misses stress/yield strength).

II. MATERIAL AND METHODS

The material of pipes was ductile iron. The chosen control parameters are summarized in table 1. The control factors were assigned to the various columns of orthogonal array (OA), L9 is given in table 2. The dimensions of notch are given in figure 4.

Table 1: Control factors and their levels

Factor	Symbol	Level–1	Level–2	Level–3
Thickness, mm	A	7.5	10.0	12.5
Length of crack, mm	B	100	150	200
Depth of crack	C	40%t	50%t	60%t
Grade of steel	D	A106	B106	C106

where t is pipe thickness

Table 2: Orthogonal Array (L9) and control factors

Treat No.	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

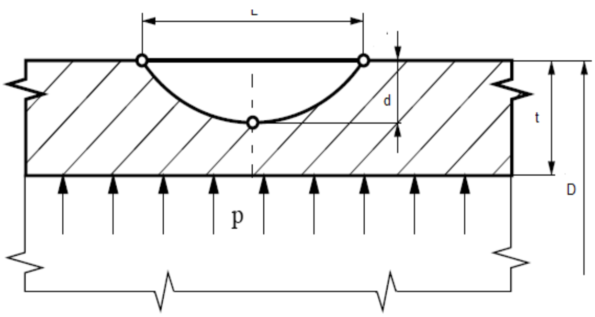

Fig. 4. The Crack dimensions.

Using Choi's criterion [24], the bursting pressure can be estimated as follows:

For $L < 6\sqrt{Rt}$

$$P_b = 0.9\sigma_m \frac{2t}{D_i}\left[C_2\left(\frac{L}{\sqrt{Rt}}\right)^2 + C_1\left(\frac{L}{\sqrt{Rt}}\right) + C_0\right] \quad (1)$$

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$$C_2 = 0.1163\left(\frac{ad}{t}\right)^2 - 0.1053\left(\frac{d}{t}\right) + 0.0292$$
$$C_1 = -0.6913\left(\frac{d}{t}\right)^2 + 0.4548\left(\frac{d}{t}\right) - 0.1447$$
$$C_0 = 0.06\left(\frac{d}{t}\right)^2 - 0.1035\left(\frac{d}{t}\right) + 1.0$$

For $L \geq 6\sqrt{Rt}$

$$P_b = \sigma_m \frac{2t}{D_i}\left[C_1\left(\frac{L}{\sqrt{Rt}}\right) + C_0\right] \quad (2)$$

$$C_1 = 0.0071\left(\frac{d}{t}\right) - 0.0126$$
$$C_0 = -0.9847\left(\frac{d}{t}\right) + 1.1101$$

where, D_i, R and t are, respectively, the inside diameter, mean pipe radius and thickness of the pipe. L and d are, respectively, crack length and crack depth.

For Choi's criterion, the von Mises criterion is the second classical yield criterion in strength theory, often referred to as the octahedral shear stress criterion. It can be expressed by the principal stresses in the form:

$$\tau_{vm} = \sqrt{\frac{1}{6}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]} = \frac{\sigma_{YS}}{\sqrt{3}} \quad (3)$$

where τ_{vm} is the von Mises effective shear stress.

The von Mises yield surfaces in principal stress coordinates circumscribes a cylinder with radius $\sqrt{2/3}\,\sigma$ around the hydrostatic axis. Intersection of the von Mises yield criterion with the σ_1, σ_2 plane, where $\sigma_3 = 0$ (Fig. 5).

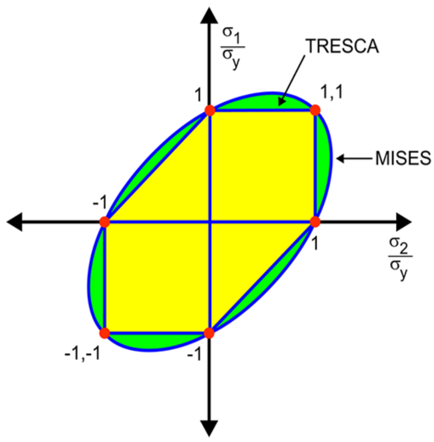

Fig. 5. Illustration of Tresca and von Mises criteria.

For a two-parameter Weibull model, the risk of rupture is of the form

$$B(s) = A\left(\frac{\sigma}{\sigma_0}\right)^\beta \qquad (\sigma_0, \beta > 0) \quad (4)$$

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where $A = \int_V [f(x,y,z)]^\beta dv$ (5)

and σ0 is the characteristic strength, and β is the shape factor that characterizes the flaw distribution in the material. Both of these parameters are considered to be material properties independent of size. Therefore, the risk to break will be a function of the stress distribution in the test specimen. Equation (8) can also be written as

$$B(\sigma) = A\left(\frac{\sigma}{\sigma_0}\right)^\beta \quad (6)$$

And the reliability function, Eq. (7) can be written as a two-parameter Weibull distribution

$$B(\sigma) = e^{-\left(\frac{\sigma}{\sigma_0}\right)^\beta} \quad (7)$$

III. RESULTS AND DISCUSSION

The bursting pressures computed from PCORRC, ASME B31G, modified ASME B31G, DNV-RP-F101, SHELL-92, RSTRENG, LG-18, Fitnet FSS and Choi criteria are given in figure 6. The results obtained using Choi's criterion were in between DNV RP F101 and PCORRC criteria. Therefore, the bursting pressures obtained through Choi's criterion are acceptable.

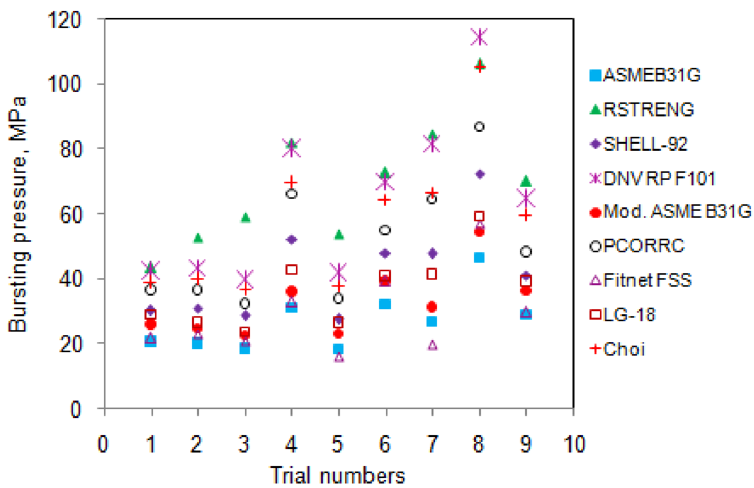

Fig. 6. Bursting pressures computed from different methods.

Table 3: ANOVA summary of the bursting pressure

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	91.80	136.71	184.06	1418.95	1	1418.95	1800516.5	57.7
B	138.95	145.29	128.32	49	1	49	62176.48	1.99
C	165.46	134.56	112.55	471.02	1	471.02	597680.88	19.15
D	110.71	6110.26	412.56	520.23	1	520.23	660123.83	21.15
e				0.003152	4	0.000788	1.00	0.01
T	506.92	6526.81	837.49	2459.203	8			100

Note: SS is the sum of square, v is the degrees of freedom, V is the variance, F is the Fisher's ratio, P is the percentage of contribution and T is the sum squares due to total variation.

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A. Influence of crack dimensions and tube material on bursting strength

Table 3 gives the ANOVA (analysis of variation) summary of bursting pressure. Even if all the process parameters could satisfy the Fisher's test at 90% confidence level, pipe thickness, crack depth and grade of ASTM 106 steels had major role in the total variation of bursting pressure. The pipe thickness (A), crack depth (C) and grade of ASTM 106 steels (D) had given, respectively, 57.70%, 19.15% and 21.15% in the total variation of the bursting pressure. The crack length (B) was insignificant.

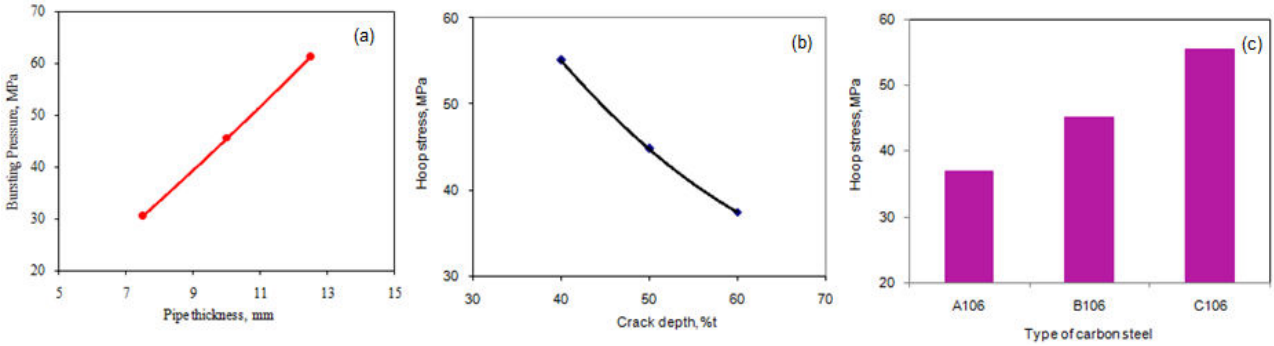

Fig. 7. Effect of pipe thickness (a), crack depth (b) and grade of steels (c) on bursting pressure.

Fig. 7a shows the dependence of bursting pressure on the pie thickness. As the pipe thickness increased the pressure required to burst the pipe would also increase. If the crack depth increased, the pipe could fail even at low bursting pressure (Fig. 7b). The required bursting pressure was high for the ductile tension grade C106 steel as compared to the other two grades (grades A106 and B106 steels). The grade A106 steel failed at low bursting pressure (Fig. 7c).

Table 4: ANOVA summary of the Tresca criterion

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	283.04	307.60	322.10	259.85	1	259.85	46185.57	6.29
B	312.46	311.69	288.59	122.65	1	122.65	21799.73	2.97
C	357.05	304.81	250.88	1878.7	1	1878.7	333918.90	45.45
D	251.13	30901.53	912.74	1872.56	1	1872.56	332827.58	45.3
e	1203.7	31825.63	1774.31	0.0225049	4	0.005626	1.00	-0.01
T	1188.5	23696.54	1629.36	4133.783	8			100

Table 5: ANOVA summary of the von Mises criterion

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	490.24	532.77	557.89	779.57	1	779.57	1254638.1	6.29
B	541.19	539.86	499.85	367.96	1	367.96	592193.94	2.97
C	618.42	527.95	434.54	5636.11	1	5636.11	9070741.9	45.45
D	434.98	92704.60	1580.91	5617.72	1	5617.72	9041145.1	45.3
e				0.002485	4	0.000621	1.00	-0.01
T	2084.8	94305.19	3073.19	12401.358	8			100

B. Failure criteria

Table 4 and 5 give the ANOVA (analysis of variation) summary of Tresca criterion and von Mises criterion respectively. Even though all the process parameters could assure the Fisher's test at 90% confidence level, only crack depth and grade of ductile iron had foremost roles in the total variation of Tresca and von Mises criteria. The crack depth (C) contributed nearly 81.41% of the total variation in the Tresca and von Mises criteria. The grade of ductile (D) put in 16.93% of the total variation in the Tresca and von Mises criteria. The pipe thickness and the crack length were insignificant in the variation of Tresca and von Mises criteria.

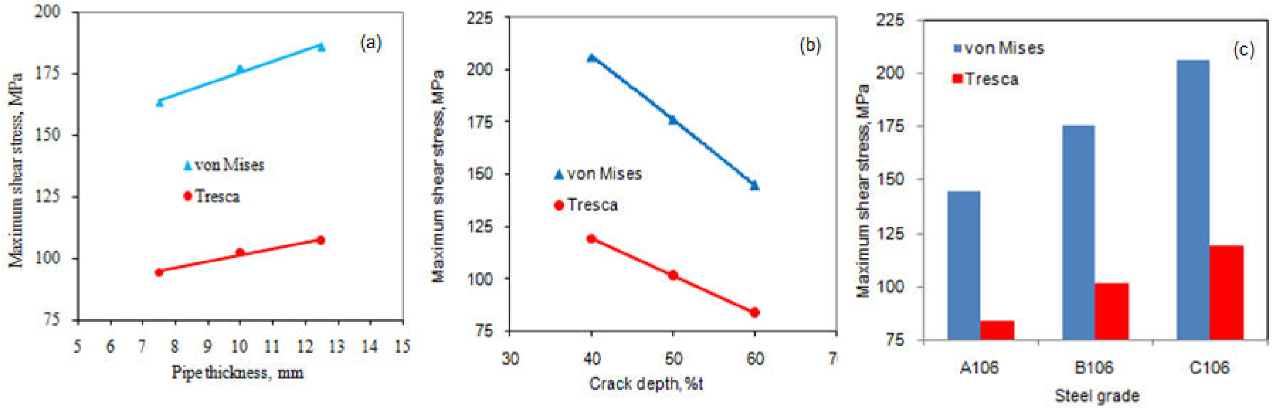

Fig. 8. Effect of pipe thickness (a), crack depth (b) and grade of steels (c) on failure criteria.

The failure shear stress increased with the increase of pipe thickness (Fig.8a). As the crack depth increased the level of failure shear stress decreased (Fig.8b). The level of maximum shear stress was low for the A106 steel grade and it was high for the C106 steel grade (Fig.8c). As observed from figure 13a, only eight pipes except pipe 8 were safe under Tresca failure criterion. From figure 13b it is observed that the pipes numbered 3 and 5 satisfy. All other pipes did not assure the von Mises failure criterion. The pipe numbered 8 did not satisfy both the Tresca and von Mises failure criteria (Fig. 9). With the increase of internal pressure, the stress variation through the ligament exhibits three distinct stages; elastic deformation, plastic deformation and material hardening.

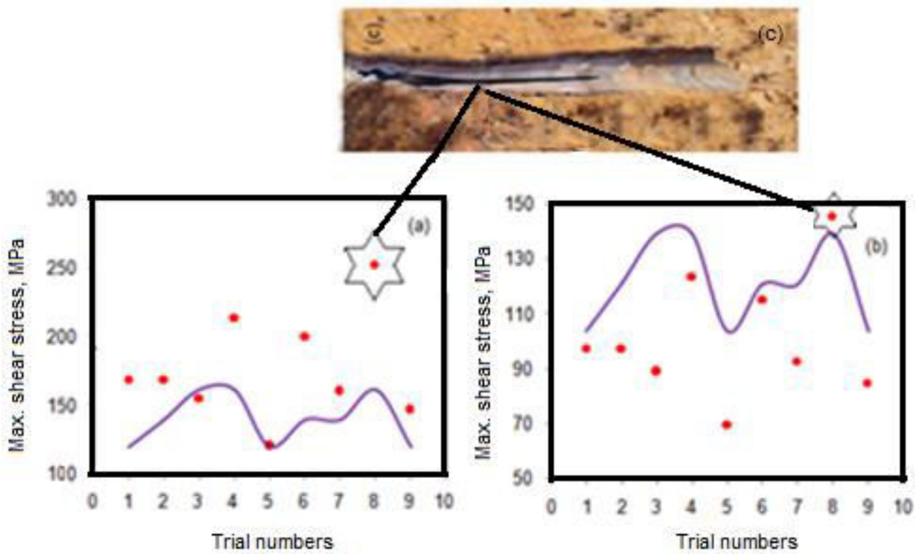

Fig. 9. Failure criterion of all pipes: (a) Tresca and (b) von Mises.

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The pipe and crack was discretized with tetrahedron elements [25] as shown in Fig. 10a. The pressure was applied inside the pipe. The von Mises stress was 312.01 MPa which was 251.28 MPa from the Choi's criterion. The stress ratio was found to be 1.25 which fails the criteria of ES/YS < 1 (where ES and Ys, respectively, are von Mises stress and yield strength) as depicted in Fig.10c. The Weibull criterion was used to predict the reliability of all the pipes. For the Choi's criterion, the reliability results were in agreement with the other popular criteria as seen in Fig.11. For 70% of reliability the maximum bursting pressure should not exceed 36 MPa.

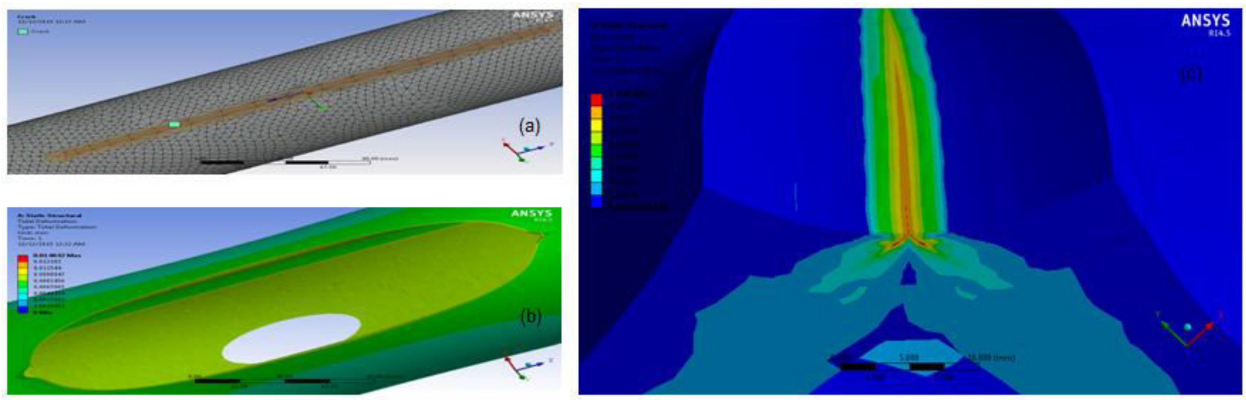

Fig.10. FEA results: (a) Discretization of pipe and crack, (b) bursting and (b) stress ratio.

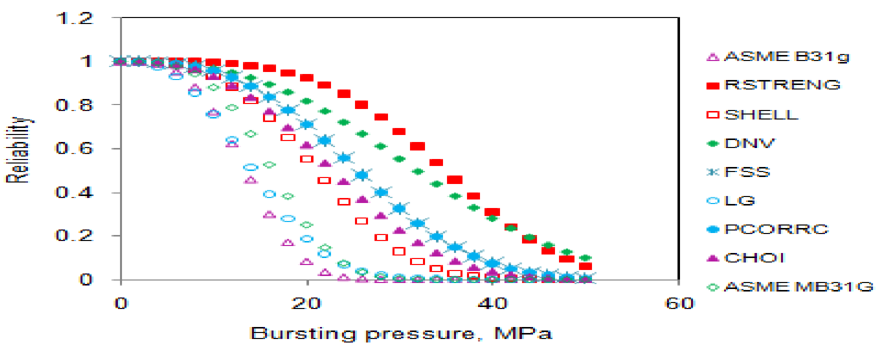

Fig.11. Weibull failure criterion of all pipes.

IV. CONCLUSIONS

The bursting pressure is highly dependent on the pipe thickness, crack depth and grade of steel. The bursting pressure increases with the increase of pipe thickness. Also, the bursting pressure decreases with the increase of crack depth. The von Mises criterion is very near the failure pattern of the pipes. The Choi's criterion criterion could predict the bursting pressure of the steel pipes employed for ammonia transport accurately satisfying the results obtained from the experimentation, finite element analysis, Weibull criterion and other popular criteria used for the estimation of the bursting strength.

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