Burst Pressure Prediction of a Maraging Steel Chamber With Surface Cracks

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ABSTRACT

As a part of development plan, to validate the fracture design/analysis procedures and to identify/characterise the flaws on actual hardware, maraging steel chambers were fabricated with a limited number of welded precracked specimens and pressure tested to burst. Theoretical evaluation of the burst pressure of the chambers are found to be in good agreement with test results.

KEYWORDS

Maraging steel; fracture toughness; surface cracks.

INTRODUCTION

Structural components generally contain crack like defects which are either inherent in the material or get introduced during fabrication process some times inducing unexpected catastrophic fracture. The increased use of modern high strength materials, while producing lighter structures tend to be more critical in the presence of defects than the traditional ductile materials. The driving need for methods which quantify the presence of cracks and their effects on performance has led to the evolution and development of fracture mechanics.

Vikram Sarabhai Space Centre (VSSC), India, has devoted much attention to the fracture control procedures for the purpose of investigating failure mechanisms applicable to thin-walled aerospace pressure vessels. A limited number of chambers were designed and fabricated out of high strength 1800 MPa grade maraging steel with an inner diameter of 560 mm and nominal thickness of 8 mm . For this programme,experiments were carriedout to generate the following data in parent and welded materials in maraged conditions

.stress-strain diagram, fracture toughness of the material and crack growth data under specified loading conditions.
.surface cracks of desired sizes in welded maraging steel plates as demanded by the design.

The chamber is a cylindrical shell with spherical end domes having intensionally introduced cracks of 3x1 mm in cylindrical part on the outer surface of the weldment. This paper provides theoretical and experimental analysis of the tested chambers. Theoretical calculations of the burst pressure of chambers are reasonably comparable with test results.

FRACTURE ANALYSIS

The performance of the structural component in the absence of cracks is assured, if the stress under service loads are less than the strength of the material whereas in the presence of cracks, the intensity of the stress at the crack-tip should be less than the fracture toughness of the material. For prediction of critical crack sizes and the life expectancy of structural components, the designer needs material properties, flaw details and applied load/environments.

The stress intensity factor is calculated from the membrane and bending stresses at the crack locations using the following equation (ASME XI,1977 ; Joint study report,1981)

$$K_I = (\sigma_m M_m + \sigma_b M_b)(\pi a/Q)^{1/2} \qquad (1)$$

where $Q = \phi^2 - 0.212\{(\sigma_m + \sigma_b)/\sigma_{YS}\}^2$; $\phi = \int_0^{\pi/2}\{1-(c^2-a^2)\sin^2 x/c^2\}^{1/2}dx$;

σ_m, σ_b are the membrane and bending stresses; σ_{YS} is the yield strength of the material; M_m, M_b are magnification or correction factors; a and c are the depth and half the length of a part-through crack.

Replacing K_I as K_{IC} (plane strain fracture toughness) in (1), one can obtain the relationship between the fracture strength, σ_f ($=\sigma_m + \sigma_b$) and the critical crack size as

$$\sigma_f = K_{IC}\,\phi\,(1+\sigma_b/\sigma_m)\{\pi a(M_m + \sigma_b M_b/\sigma_m)^2 + 0.212\,(1+\sigma_b/\sigma_m)^2(K_{IC}/\sigma_{YS})^2\}^{-1/2} \qquad (2)$$

Chell(1979) has examined the nondimensional fracture strength versus critical crack sizes through theoretical and exeperimental results. It is suggested that if one draws a tangent from the ultimate tensile strength (σ_{ult}) to the theoretical fracture strength curve, the experimental data for the structural components are expected to lie above the tangent line or on the theoretical curve, which is used as fracture strength curve in design.

In actual service, it is likely the vessels are of thin shell catagory and that at the crack-tip the assumptions of plane strain conditions are not applicable. In this case the prediction of life expectancy/failure is governed by K_C (critical stress intensity values corresponding the material and size) which can be determined from crack growth resistance curve(R - curve) of the material.

The relation between the stress intensity factor, K_{max} and the nominal stress, σ_f at failure established by Nageswara Rao and Acharya(1988) using R - curve is

$$K_{max} = K_F\{1 - m(\sigma_f/\sigma_u) - (1-m)(\sigma_f/\sigma_u)^p\} \qquad (3)$$

where K_F, m and p are the fracture toughness parameters. σ_u is the nominal ultimate failure stress. The value of σ_u for different configurations are given in the articles by Newman (1976a,b).For pressurised cylinders, $\sigma_u = 1.15\,\sigma_{ult}$, determined by calculating the nominal stresses required to satisfy the Von-Mises yield criterion of failure assuming a 2:1 biaxial stress ratio. In general, K_{max}, for any cracked configurations can be expressed from (1) as

$$K_{max} = \sigma_f\{M_m + \sigma_b M_b/\sigma_m\}(\pi a)^{1/2}/\phi \qquad (4)$$

Using (3) and (4), one can write (5) to determine the nominal failure stress (σ_f) for a specified crack size as

$$(1-m)(\sigma_f/\sigma_u)^p + [m + \sigma_u\{M_m + \sigma_b M_b/\sigma_m\}(\pi a)^{1/2}/\phi K_F](\sigma_f/\sigma_u) - 1 = 0 \qquad (5)$$

Newton-Raphson method can be used to solve (5) for σ_f.

Theoretical calculations based on (5) are verified with the residual strength measurements of the surface cracked maraging steel plates under tension ($\sigma_b = 0$) and are presented in Fig.1. The results are found to be in good agreement to experimental results.

The crack growth data with repeated waveform loading as expected to occur in actual service (Fig. 2), generated from laboratory specimens are used in Paris crack growth equation

$$da/dN = c\,(\Delta K)^n \qquad (6)$$

to determine the material constants c and n. Integrating (6), a relation between K_I/K_{IC} and the number of cycles to failure can be obtained.

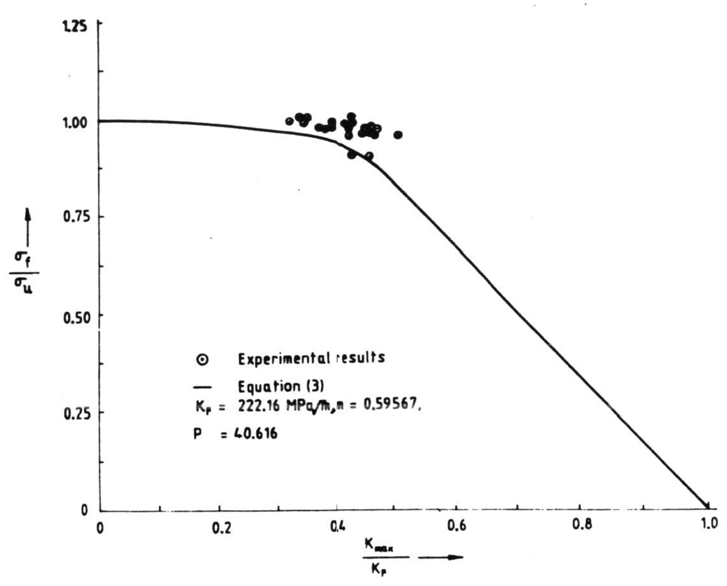

Fig.1. Comparison between theoretical and experimental results of K_{max} and σ_f for centre surface cracks in maraging steel welded plates under tension (Nageswara Rao and Acharya, 1988).

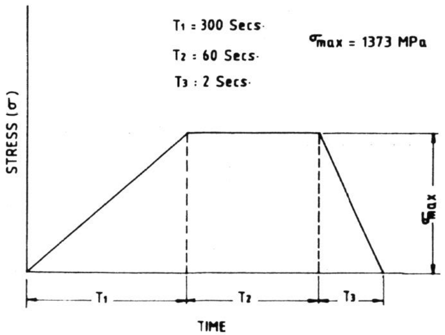

Fig.2. Wave form loading for crack growth studies.

FRACTURE STUDIES ON MARAGING STEEL CHAMBER

To validate the above prediction methods for application to actual design, a chamber was designed (Vinod Kumar,1986) as shown in Fig. 3 using 1800 MPa grade maraging steel. Three fatigue cracks of 3 x 1 mm built in the chamber at the weldment were identified as A, B and C. The cylindrical part and domes of the chamber were realised through roll bending, dishing respectively and subsequent machining and TIG welding. The fabricated chambers underwent elaborate quality control and inspection procedures including radiographic, ultrasonic testing and holography to identify and characterise the flaws.

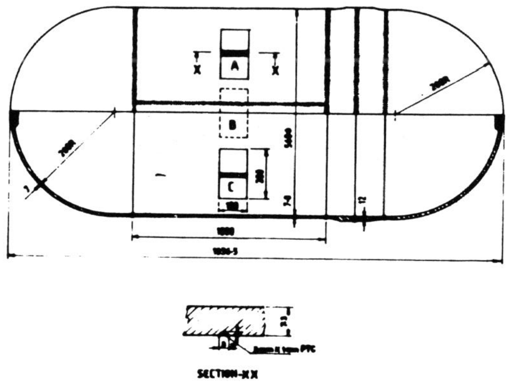

Fig. 3. Maraging steel test chamber.

For the minimum guaranteed weld material properties namely the plane strain fracture toughness, K_{IC} = 81 MPa $\sqrt{m}$, the ultimate tensile strength, σ_{ult} = 1589 MPa , the yield strength, σ_{YS} =1554 MPa, and the crack size of 3 x 1 mm, the minimum burst pressure using (2) was worked out to be 38 MPa. The chamber with strain gauge, crack gauge instrumentation was positioned in the pressure test enclosure (Fig. 4) and oil was pumped into the chamber to pressurise. The chamber was pressurised to 31.4 MPa for ten cycles and later on pressurised till burst. The chamber failed at 45.4 MPa through fast fracture at crack A in the longitudinal direction and this propagated subsequently through the parent metal. Tearing had also occurred at some locations. The failed chamber is shown in Fig. 5.

The second chamber of same design was pressure cycled at 35.8 MPa for ten cycles, and later on pressurised to burst. When the pressure reached 48.95 MPa, fast fracture occurred in the longitudinal direction of the crack B and propagated through parent metal indicating similar behaviour of fracture as observed in the first chamber.

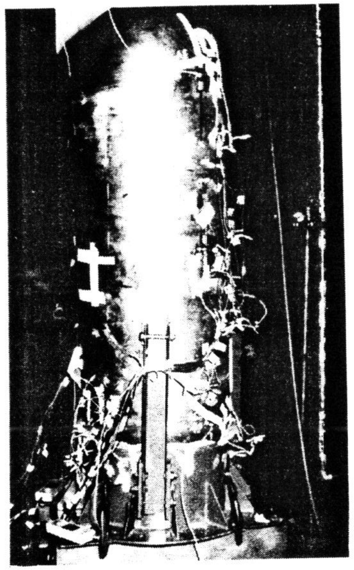

Fig.4. Test chamber with instrumentation.

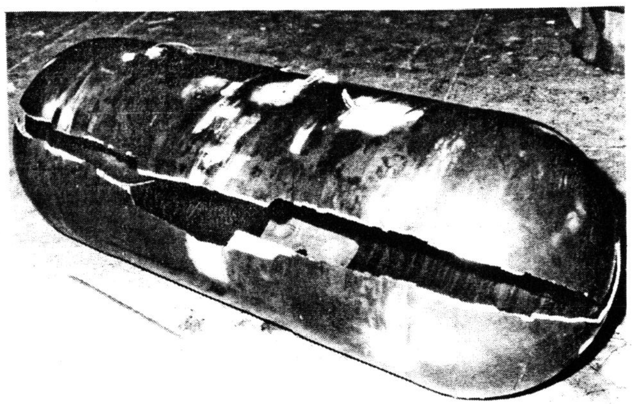

Fig.5. Test chamber after the burst test.

Fractured surface analysis of the tested chambers was carried out using Scanning Electron Microscope (Diwaker et al.,1987). This study reveals heavy depression at the end of the crack-tip indicating formation of significant plastic zone. Overall bulging was noticed before bursting occurred. The fracture surface just below these cracks were slant.

RESULTS AND DISCUSSIONS

The measured initial size of the crack for these two chambers are given in table 1. The determined fracture toughness parameters from R - curve are K_F = 222.16 MPa $\sqrt{m}$, m = 0.5957 and p =40.62 respectively. The material constants in Paris crack growth rate equation (6) are c = 0.549E-10 and n = 2.624. The units for da/dN and ΔK for obtaining the above material constants c and n are m/cycle and MPa $\sqrt{m}$ respectively. The ultimate value of nominal stress, σ_u for the test chamber using the stress-strain diagram of the material is obtained following the elastio-plastic analysis and simple instability theory (Margetson,1978).Biaxial gain (B.G.) of this chamber is worked out to be 13%. The value of σ_u for the test chamber is 1.13 σ_{ult} . The number of cycles to failure under proof pressure is obtained by integrating (6). It is found to be 90.

From these data, theoretical calculations are made to obtain fracture strength, σ_f using (2) and (5). The determined burst pressure of these chambers are presented in table 2.The weakest link in the pressure tested chambers having nominal thickness of 8 mm are in the location of cracked specimens possessing lower thickness of 7.3 mm and fracture of the chamber expected to be initiated from these cracked specimens.The mechanical properties,viz.,fracture toughness (K_{IC}),yield strength(σ_{ys}) and the ultimate strength(σ_{ult}), presented in table 1 indicate the fracture of the chambers should initiate from the crack of specimen A for the first chamber and the crack of specimen B for the second chamber.Since the minimum number of cycles to failure under proof pressure is worked out to be 90, there is no appreciable crack growth taken place in the proof pressure testing of the two chambers for ten cycles.

Conservative estimation on the burst pressure of the two chambers is noticed in the results presented in table 2, using (2) with the actual measured dimensions of the crack sizes whereas the analytical results using (5) are found to be within 10% to test results. The discrepancy in analytical and experimental results may be due to cyclic pressure loading which sometimes make the crack-tip to become blunt as we observed in the laboratory tested specimens or it may be due to variations in the mechanical properties.

Table 1 . The measured initial crack sizes of the tested chambers (thickness of cracked specimens, t = 7.3mm).

Chamber	Cracked Specimen	Material properties σ_{ult} (MPa)	σ_{ys} (MPa)	K_{IC} (MPa$\sqrt{m}$)	Initial crack size 2cxa (mm)
I	A	-	-	83.00 89.55	3.2 x 1
	B	1661	1594	88.60 90.20	2.7 x 0.9
	C	-	-	91.63 95.77	2.5 x 0.9
II	A	1676	1628	91.17 91.80 94.21	2.82 x 0.8
	B	1560	1508	77.84 89.95 90.74	2.9 x 0.9
	C	1640	1598	86.72 92.90	2.81 x 0.82

Table 2. Burst pressure calculations of the tested chambers (D= 560mm, diameter) using (5).

Chamber	Cracked specimen (t=7.3mm)	Crack size 2c x a (mm)	Analytical results σ_u (MPa)	σ_f (MPa)	P_b (MPa)	test results P_b (MPa)
I	A	3.2 x 1	1884	1795 (1517-1561)*	46.8 (39.3-40.4)	45.42
II	B	2.9 x 0.9	1763	1704 (1451-1519)	44.4 (37.8-39.6)	48.95

* results in parenthesis are obtained using (2).
Note: σ_u = (B.G.) σ_{ult} : $P_b = 2\sigma_f t / D$

CONCLUDING REMARKS

Fracture strength evaluation of thin-walled cracked configurations from (2) using the plane strain fracture toughness, K_{IC} yields conservative estimation. Since, the thickness effect on fracture toughness parameters, K_F ,m and p in (5), theoretical calculations of the burst pressure of the chambers considering the biaxial gain (B.G.) through ultimate nominal failure stress, σ_u (= (B.G.) σ_{ult}) show good correlation with test results.

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