Defence Science Journal, Vol. 65, No. 1, January 2015, pp. 83-89, DOI : 10.14429/dsj.65.7800

Structural Integrity Analysis of a Battle Tank Gun Barrel during Service

Shahnawaz Ahmad* and Vikas Kumar

Defence Metallurgical Research Laboratory, Hyderabad – 500 058, India

**E-mail: sa_drdo@rediffmail.com*

ABSTRACT

In the present investigation, failure assessment diagram (FAD) using R6 approach has been established for structural integrity analysis of a battle tank gun barrel. FEM based modelling was carried out to evaluate maximum stresses in the barrel section during firing. A detailed sensitivity analysis of various geometres, service and material parameters has been performed to assess their criticality on overall safety of the structures. The study has been carried out using actual material and firing data of a battle tank gun barrel and therefore it can give useful insight to a designer while selecting a material and designing a similar component.

Keywords: Fracture toughness, failure assessment diagram, reserve factor, finite element method, sensitivity analysis

NOMENCLATURE

FAD	Failure assessment diagram
CTOD	Crack tip opening displacement
K	Elastic stress intensity factor
K_{mat}	Materials fracture toughness
P	Operating load
P_L	Plastic limit load for flow stress equal to 0.2% proof stress of material
K_r	K/K_{mat}
L_r	P/P_L
Ø	Shape factor
σ_{flow}	Flow stress
K_{IC}	Plane strain fracture toughness
J_{IC}	Elastic plastic fracture toughness
Δa	Crack extension

1. INTRODUCTION

Safety of a structure for the intended life cycle is of prime concern for a designer, especially for critical applications such as defence, nuclear, and space where structure has to operate under complex loading and hostile environmental conditions. Under such conditions, a prior assessment of structural integrity, before the actual component is exposed to such hostile environment, becomes an indispensable task for the designer. Fast fracture in cannons and gun barrels are well reported in literature due to their large section size under plane-strain conditions[1]. In some cases, due to high instantaneous operating stress-temperature pulse, chances of elastic-plastic fracture or plastic collapse are not ruled out. Each of three fundamental fracture processes - fast fracture, fatigue and environment-assisted fracture have been the critical modes of failures in barrels during their service life. Hence, it is important to perform structural integrity analysis of gun barrel under service loading conditions to ensure safety.

The selection of an appropriate approach for structural integrity assessment depends on the mode of failure (fracture, fatigue, corrosion or creep), type of the component, and service conditions. Cracking phenomenon leads to many times decrease in strength and is peculiarly dangerous, especially for brittle materials[2]. Some of the approaches are specific to a certain industry, whereas others have more general applications. Considering all these parameters, here a battle tank gun barrel has been assessed for structural integrity during firing using well established R6 approach. The R6 approach is utilised as it has extensively used the principles of applied fracture mechanics in evaluating the structural integrity of components.

As a known conventional design approach uses strength-based criteria where to avoid failure, maximum applied stress should not exceed a certain fraction of the yield strength. This statement is based on the assumptions that, (a) the component is free from any flaws and defects, and (b) the safety factor would compensate for any unexpected overloading or deterioration of the component during its service life. Components including welded joints in engineering structures, e.g., bridges, car chassis or pressure vessels may contain flaws and defects, which can compromise on the strength of the structure drastically.

Until early 19th century, design engineers relied on using large safety factors to overcome the uncertainty associated with the actual strength of various components and their joints due to inevitable and undetectable internal defects. R6 is a technique to assess the design in the presence of defects or flaws. R6 procedure is a widely used technique in Europe and is well adopted by British Energy[3] which uses this two-criterion approach for analysing its equipment, it is two criteria approach as it evaluates structure under two major failure modes, i.e., fast fracture and plastic collapse. This technique is also used by known researchers in pressure vessel and piping industries[4].

Received 25 June 2014, revised 7 November 2014, online published 27 February 2015

1.1 Development of Failure Assessment Diagram based on R6 Approach.

Some of the similar general procedures which carry wide industrial applications are as follows:

(a) Structural Integrity Assessment Procedure for European Industry (SINTAP)[5]

(b) Engineering Treatment Model (ETM)[6]

(c) BS 7910 (British Standards flaw assessment procedure)[7]

(d) R5 Approach (Assessment procedure when creep becomes significant)[3]

The R6 approach has been continually evolved since 1976 with up-to-date advances in fracture mechanics and related development elsewhere in the world.

1.2 R6 Approach

The structural integrity of components by R6 method is assessed under two extreme failure modes i.e., plastic collapse and fast brittle fracture. Plastic collapse is controlled by overall plasticity in the defect containing section and fast fracture by the local crack tip stress-strain fields dictated by stress intensity factor, K. The R6 method characterises fracture in terms of two normalised parameters, namely, K_r and L_r which depend on the applied load, material properties, and crack geometry[8]. These can be defined as, $K_r = K / K_{mat}$ and $L_r = P / P_L$, where K is the elastic stress intensity factor at operating load P, K_{mat} is the material fracture toughness and P_L is the plastic limit load for a flow stress equal to 0.2% proof stress of the material. The assessment point (L_r, K_r), which is computed for a component under operating loading conditions, is plotted on the failure assessment diagram (FAD) and compared with the boundary defined by the function $K_r = f(L_r)$ between limit $K_r = 1$ and plastic collapse limit $L_r = L_{r,max} = 1.2$ (Fig. 1) Here $L_{r,max}$ is also represented as the ratio of a flow stress to the yield stress and allows for strain hardening beyond yield[10]. If the point lies inside the curve, then the structure is considered safe. If it lies on or outside the curve, the possibility of failure must be conceded and remedial action be performed.

In the present analysis, FAD has been developed for a thick walled battle tank gun barrel fabricated by an electro-slag-refined (ESR) medium carbon, quenched and tempered steel. Among the three recommended options in R6 procedure, the 'Option 2', which is based more on material's specific deformation characteristics, has been used for defining the failure assessment curve:

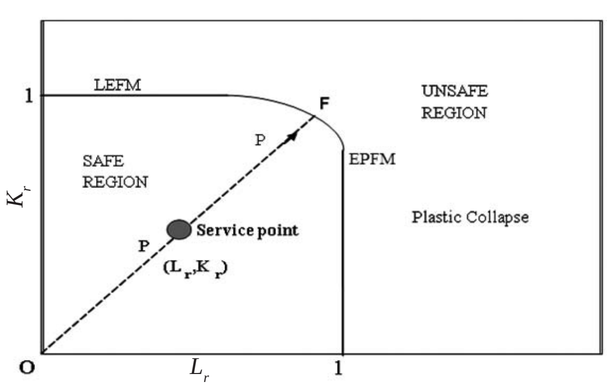

Figure 1. A schematic of failure assessment diagram.

$$K_r = \left\{ \frac{E\epsilon_{ref}}{L_r \sigma_y} + \frac{L_r^{\,3}\sigma_y}{2E\epsilon_{ref}} \right\}^{1/3} \tag{1}$$

where $(\varepsilon_{ref}, \sigma_{ref})$ are the coordinate points on the materials true stress-true strain curve and $L_r = \sigma_{ref} / \sigma_y$. The experimental database on tensile and fracture toughness, both in terms of plain strain fracture toughness (K_{IC}) and elastic-plastic fracture toughness (J_{IC}), have been generated on standard test specimens as per ASTM standard ASTM-E-399[11] and E-1820[12]. The assessment point (L_r, K_r) has been calculated for typical operating conditions encountered by the barrel using FEM based simulations in which stresses in the barrel is evaluated through linear static analysis using axis-symmetric CAD model. A MATLAB program is generated using the given constitutive equations in developing FAD. The location and proximity of the assessment point with respect to the FAD boundary defines the reserve factor which is an indicator of safety of the component under operating loading conditions.

1.2.1 Evaluation of Service Point

$$K_r = \frac{K_{app}}{K_{mat}} \quad \text{and} \quad L_r = \frac{P_{app}}{P_{CL}} \tag{2}$$

where K_{mat} is the fracture toughness of the material, P_{app} the applied loading, P_{CL} the plastic collapse limit load, and K_{app} the applied stress intensity factor.

(i) The applied stress intensity factor, K_{app} is calculated by the standard fracture mechanics expression for a surface flaw case :

$$K_{app} = \frac{\left(1.12 \times \sigma_{app} \times \sqrt{\pi \times a \times 0.001}\right)}{\sqrt{\left(\Phi^2 - 0.12 \times \frac{(\sigma_{app})^2}{(\sigma_{ys})^2}\right)}} \tag{3}$$

where

$$\Phi = \frac{3\pi}{8} + \frac{\pi a^2}{8c^2} \tag{3a}$$

Φ is the shape factor and it depends on crack geometry.

(ii) The plastic collapse load P_{CL}, has been determined by a standard expression used for pressure vessels.

$$P_{CL} = \frac{\sigma_{flow} \times \left(1 - \frac{a}{t}\right)}{\left(\frac{r}{t} + \frac{a}{t}\right)} \quad \textit{for thick cylinder} \tag{4}$$

$$P_{CL} = \frac{\left\{\sigma_{flow} \times \left(1 - \frac{a}{t}\right) \times t\right\}}{\left\{\left(1 - \frac{a \times m^2}{t}\right) \times r\right\}} \quad \textit{for thin cylinder} \tag{5}$$

where σ_{flow} = flow stress $= \frac{(\sigma_{uts} + \sigma_{ys})}{2}$ σ_{app} = applied stress, m = bulging factor which is the ratio of stress intensity factor of curved surface to the stress intensity factor of plane surface. It compensates for out of plane deformation on a curved surface of pressure vessel.

(iii) A semi-elliptical surface flaw with crack plane perpendicular to hoop stress direction of the pressure vessel, a most critical case, has been considered for a non-conservative analysis. As per the user experience and available NDT level-E(I), aspect ratio of crack taken as ½, with a = 0.5 mm and 2c = 1.27 mm, is used to calculate the shape factor from Eqn. 3(a).

2. EXPERIMENTAL PROCEDURE

Mechanical tests were performed on gun barrel steel to evaluate various material parameters which are used in FAD analysis, namely, Young's Modulus (E), yield strength (σ_{ys}), tensile strength (σ_{UTS}), and fracture toughness (K_{IC}), etc.

2.1 Fracture Toughness Testing

First tensile tests were conducted to evaluate basic material properties, and subsequently the fracture toughness tests were carried out using some of those properties. Plane-strain fracture toughness (K_{IC}) is one of the important input parameters for development of FAD. In case of quenched and tempered gun barrel steels, thickness required as per ASTM standard ASTM-E-399 for valid K_{IC} is ~ 45 mm, thus requiring large sized Compact-Tension (CT) specimens to be tested beyond the existing machine capacity. Hence, elastic-plastic fracture toughness parameter J_{IC} has been evaluated as per ASTM standard E-1820 which requires a specimen of comparatively lower thickness. The measured J_{IC} value has been used to calculate K_{IC} by the expression:

$$K_{IC} = \sqrt{\frac{J_{IC} \times E}{(1-\upsilon^2)}} \tag{6}$$

where υ is the poissons ratio and E is the Youngs modulus of the material.

The 1TCT specimen configuration has been used to measure J_{IC} of the steel using INSTRON-8500servo hydraulic test system. The 1TCT (thickness, B=25.4 mm) specimen configuration meets the thickness validity criterion: $B > 25 * J_{IC} / \sigma_{flow}$ as per ASTM E-1820 standard, where σ_{flow} is average of σ_{ys} and σ_{UTS}. The specimens were extracted from the gun barrel section along an orientation for which loading direction matches with the hoop stresses operating in the gun barrel, as shown in Fig. 2. Prior to the testing, all the specimens were fatigue pre-cracked and side-grooved as per the standard. The single specimen technique based on elastic unloading compliance method was used for this purpose. The method involves pin loading of fatigue pre-cracked specimens and determination of J as a function of crack extension. Load verses load-line displacement was recorded digitally. The standard ASTM expressions as per E-1820 prescribed for CT specimen were used for calculation of J and crack length by compliance equation. The J values were plotted against physical crack growth, Δa_p, using at least four data points within the specified limits of crack growth. The J vs crack extension plot (J-R curve) is approximated with a best-fit power-law relationship[13]. A blunting line is drawn, approximating the crack tip stretch effects. A 0.2 mm offset line, parallel to the blunting line is drawn, the intersection of this line with the power law fit of J-Δa data pairs defines J_{IC} provided the following validity requirements of this test method are satisfied[14,15]:

i) Thickness (B) should be greater than $\dfrac{25 \times J_Q}{\sigma_{flow}}$

ii) Initial ligament (W-a_0) should be greater than $\dfrac{25 \times J_Q}{\sigma_{flow}}$

iii) Regression line slope should be less than σ_{flow}

To delineate the crack extension due to monotonic loading during J_{IC} testing from the pre-existing fatigue pre-crack and fast fracture regime, the specimens were subjected to a prescribed heat tinting process for steels. For heat-tinting, the specimens were heated in a furnace at about 300 °C, generally recommended for steels, for an hour and air cooled. A typical fracture surface of heat-tinted specimen is shown in Fig. 3. The various crack extension regimes are clearly visible as marked on the specimen surface. In most of the cases, no notable difference in compliance predicted and physically observed crack length was observed. A series of specimens were tested to arrive at a reproducible J_{IC} value.

A typical J-R curve which is a plot between J and crack extension (ΔCL) is shown in Fig. 4. The fracture toughness

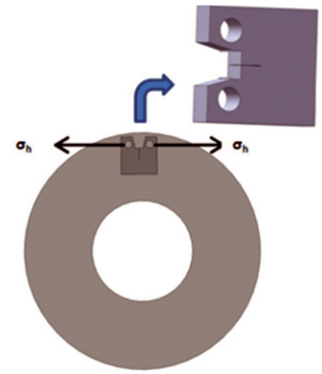

Figure 2. Orientation of CT specimen extracted from the gun barrel cross section.

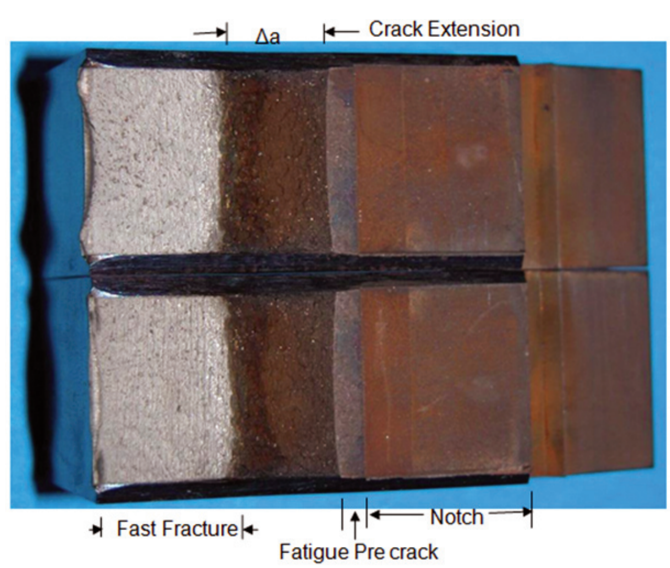

Figure 3. Heat-tinted CT specimen of gun barrel after fracture toughness testing.

K_{mat} has been calculated using the expression (6), which yields a value of ~145 MPa√m.

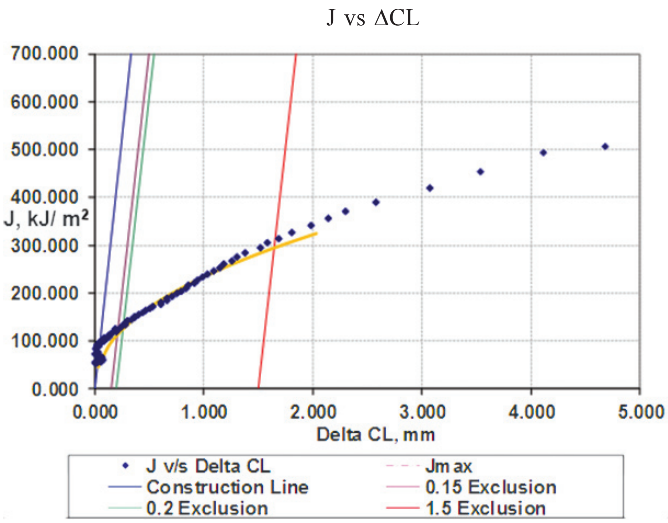

Figure 4. Experimentally obtained J_R - ΔCL Curve.

2.2 Fatigue Crack Growth Rate (FCGR) Testing.

In order to assess the integrity of the gun barrel during continuous firing, the fatigue crack growth data are generated on compact tension specimens as per ASTM E-647[16]. Fig. 5 shows FCGR curve in terms of crack growth rates (mm/cycle), da/dN as a function of stress intensity factor range, ΔK for gun barrel steel at ambient and elevated temperature. Though the instantaneous temperature during firing is very high, it acts for a very short while and the associated time is less than material response characteristics. The average gun barrel temperature for most of the time during firing is maintained closely at 150 °C, though for this type of quenched and tempered steel, mechanical properties are not expected to vary at this temperature. Based on Paris equation $(da/dN = C\Delta K^m)$ thus established experimentally for this steel and using FCGR data generated at average service temperature, the fatigue crack growth in the gun barrel has been simulated and superimposed on the failure assessment diagram:

$$\frac{da}{dN} = 0.64\times10^{-8}\left(\Delta K\right)^{3.1} \tag{7}$$

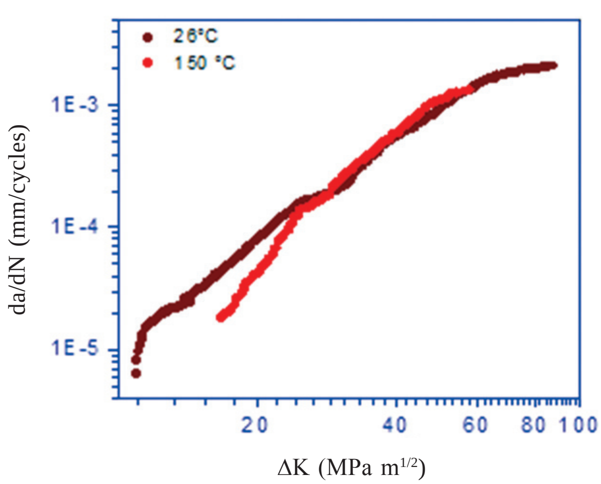

Figure 5. da/dN vs ΔK curve for gun barrel steel.

3. RESULTS AND DISCUSSION

In the present analysis, propensity of failure of gun barrel in terms of FAD, either by brittle fracture or by plastic collapse, has been assessed based on R6 approach for the typical operating loading conditions. After developing FAD for these components, a detailed sensitivity analysis has been performed to assess criticality of various service, design and material parameters. The three sets of basic input data - material data, geometry data and design data are used apart from simulation results for the assessment of service point (L_r, K_r) and FAD curve (Table 1). In addition, true stress-true strain data are provided as input toin-house developed MATLAB program in performing R6 analysis based on the selected Option-II, as discussed earlier. The program finally provides a graphical representation of FAD indicating locus of service point with respect to the failure boundary and safety margins.

Table 1. Material, Geometry and Design data of Gun barrel

Material data(RT)	
Material	ESR processed gun barrel steel
Yield strength (MPa)	1162
UTS (MPa)	1224
Young's modulus (GPa)	210
Fracture toughness (MPa-√m)	145
Geometry data	
Component geometry	Pressure vessel
Inner diameter of chamber section (mm)	164
Outer diameter of chamber section (mm)	308
Length of chamber (mm)	628
Length of Barrel (mm)	5771
Design data	
Max proof pressure (MPa).	610 ± 10
Normal service pressure (MPa)	510 ± 10
Crack geometry	Semi-elliptical surface crack
a (mm)	0.50
2c (mm)	1.27

3.1 Determination of Service Point

For determination of the service point, it is important to know the typical operating internal pressure distribution along the axis of the gun barrel during firing. The pictorial view of the barrel has been given in Fig. 6. Chamber portion of the barrel is the place where ignition of the charge takes place. The ignition of the charge is known to cause sudden increase in pressure in the chamber, for several milliseconds followed by violent thermal flash. Therefore, the build up pressure is expected to be maximum inside the chamber section and it diminishes exponentially as the gas expands towards the muzzle end. The variation of firing pressure along central axis of barrel based on field trials is also shown in Fig. 6. Since the chamber region is encountering the maximum pressure and temperature, and

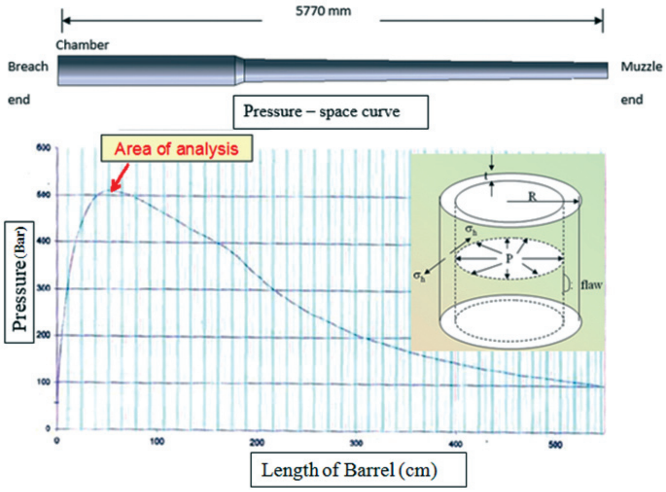

Figure 6. Firing pressure variation along the length of gun barrel.

also based on earlier firing data, it is more failure-critical, and hence selected as most critical region for the integrity analysis. For determination of service point (L_r, K_r), the applied stress σ_{app} is evaluated at chamber section at the operating pressure.

3.2 Determination of Stresses in the Barrel

Stresses in gun barrel have been determined by FEM-based linear static analysis using ANSYS tool. The Axis-symmetric breach section of the model is meshed with PLANE-82 element, geometrically constrained along U_y and loading conditions are applied from breach to muzzle end.

The maximum stress was recorded at the inner surface of the chamber is of the order of ~1200 MPa as shown in Fig. 7. The maximum stress as predicted by FEM matches closely with that calculated by the classical analytical theory. It has also been noticed that a large stress is found at the point where the chamber section ends and the internal volume converges. It may be due to a point of singularity, i.e., high stress region, which is created due to sharp change in volume of the section at chamber. It has also been noted that at some locations, the

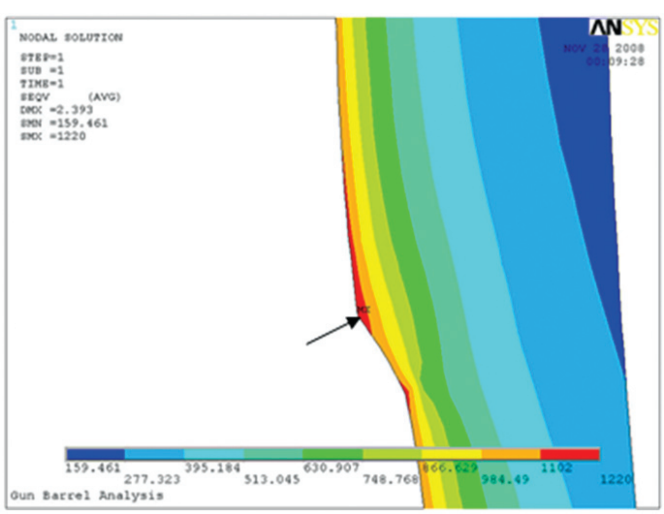

Figure 7. Von-Mises stresses at chamber section.

stresses may exceed the yield strength of the material. But these high stresses are local in nature and dissipate rapidly; thus, causing a redistribution of stress. Thus, there will be a redistribution of stress from high stressed region to the nearby low stressed region. These high stresses may cause local micro-yielding, leading to slight plastic deformation in the vicinity of high stress region. This deformation would increase the contact area over which the pressure is acting, which in turn reduces the stress. Field experience on pressure vessels has shown that these stresses are secondary in nature and are allowed to exceed the yield stress without affecting the structural integrity of the component provided the area on which it is acting is small.

3.3 Failure Assessment Diagram

Since the gun barrel experiences high pressure and temperature on the innermost circumferential fibre, there is ample probability of development of a surface flaw during service. Therefore, an elliptical surface flaw perpendicular to the loading has been assumed at the internal surface and service parameters are determined. After establishing service point (L_r, K_r) as (0.18, 0.1) corresponding to the operating hoop stresses of 1090 MPa, FAD has been drawn from material's true stress–true strain curve using expressions 1-5 up to a maximum L_r level of 1.2, as recommended in R6 procedure for high-strength steels.

3.4 Sensitivity Analysis

Sensitivity analysis has been performed for gun barrels to assess the criticality of various design, service and material parameters on there structural integrity. Further, the relative movement of service point within the safe zone with respect to the FAD boundaries also indicates the modes of failure, i.e., brittle fracture or plastic collapse.

The various design parameters–radius and thickness of the gun barrel, service parameter–internal pressure, and material properties–fracture toughness, yield strength, and UTS have been varied within ± 20% range from their nominal values. At a time, only one single parameter has been varied, keeping all others constant. FAD has been generated under various conditions using MATLAB for these given parameters, its graphical representation is drawn below for two important cases. The locii of these service points show whether the change in these properties is taking the system towards fast fracture or plastic collapse. For example, a decrease in thickness of barrel will make the service point move towards point marked as 2 in FAD of Fig. 8 which implies that decrease in thickness influences both the failure modes, i.e., plastic collapse and fast brittle fracture. Similarly in Fig. 9, the decrease in fracture toughness is making the service point move towards point marked as 2 in FAD which implies a low fracture toughness will render the barrel more prone to fast fracture. Similarly, the internal operating pressure also moves the service point along the line OF exhibiting marginal tendency towards brittle fracture region.

Variation in tensile properties like yield strength and UTS moves the service point horizontally towards plastic collapse line. Finally an envelope of service points has been generated on the FAD for various normal-to-extreme loading conditions and it has been found that the envelope falls well within the safe regime in FAD, depicting the barrel to be safe under given service, conditions as shown in Fig. 10.

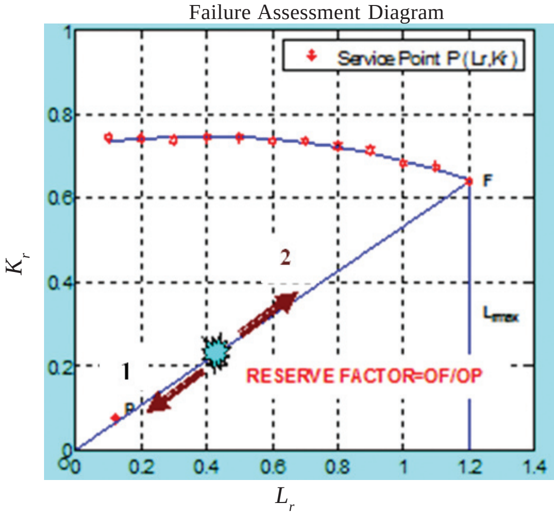

Figure 8. FAD showing effect of thickness of barrel.

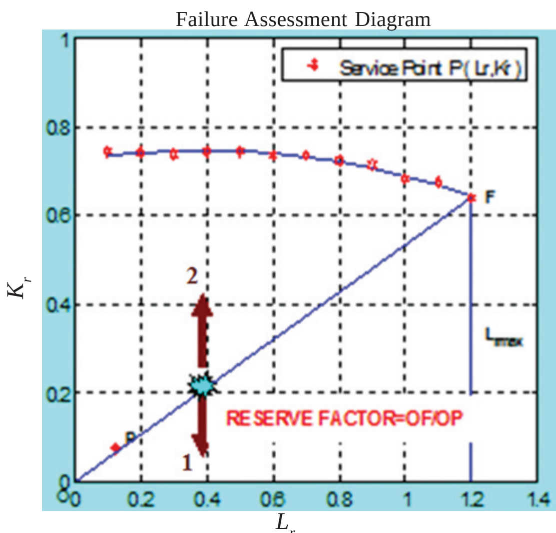

Figure 9. Effect of fracture toughness.

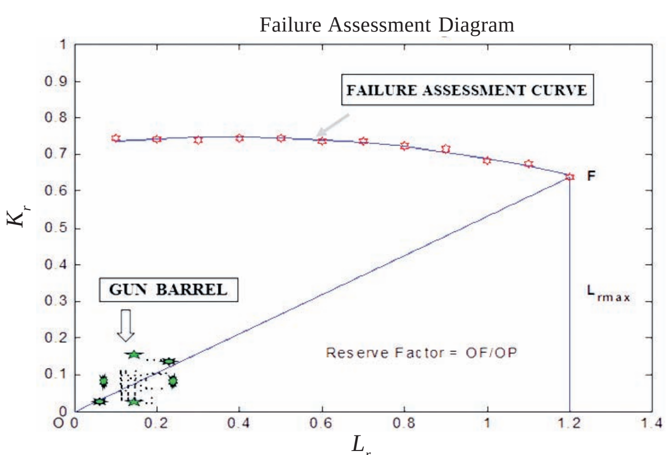

Figure 10. Envelop of service points in FAD.

4. CONCLUSIONS

The service point in FAD is found to lie within the bounding curves with fairly high reserve factor ~ 8, owing the gun barrel to be safe under the given loading conditions.

Stresses are maximum at the sharp converging section inside the barrel which act as stress raiser site which may give rise to crack nucleation and thus need to be designed carefully for safe functioning of the barrel.

The sensitivity analysis shows that various design, service, and material parameters affect the integrity of the structure considerably. Among these, the fracture toughness is found to be the most critical parameter, and which is required to be controlled to ensure safe performance of any structure, especially when it is used for a critical application like gun barrel.

ACKNOWLEDGEMENTS

Financial assistance from Defence R & D Organization is gratefully acknowledged. The authors are thankful to Director DMRL for his guidance and permission to carry out this work. They are also thankful to Ordnance Factory (MSF), Ishapore, and Armament Research and Development Establishment (ARDE), Pune, for providing important information for carrying out this work.

REFERENCES

1. Underwood, John H. & Troiano, Edward. Critical fracture processes in army cannons: A review. *J. Pressure Vessel Techno.*, 2003, **125**(3), 287-92. doi: 10.1115/1.1593075
2. Mahdavinejad, R.A. Prediction of cannon barrel life. *J. Achiev. Mater. Manuf. Eng.*, 2008, **30**(1), 11-18.
3. Harrison, R.P.; Loosemore, K. & Milne, I. Assessment of the integrity of structures containing defects, CEGB Report R/H/R6, UK, **1976.**
4. Ainsworth, R.A. Failure assessment diagram methods, Chapter 7.03, **2003**. pp. 89–132.
5. Webster, Stephen & Banister, Adam. Structural integrity assessment procedure for Europe: The SINTAP programme overview. *Eng. Fract. Mech.*, 2000, **67**(6), 481-14. doi: 10.1016/S0013-7944(00)00069-2
6. Schwalbe, K.H.; Zerbst, U.; Kim, Y.-J.; Brocks, W.; Cornec, A.; Heerens, J. & Amstutz, H. The ETM method for assessing crack-like defects in engineering structures, EFAM ETM 97, GKSS Report 98/E/6, GKSS Research Centre, Geesthacht, 1998.
7. Standard BS 7910, Guide on Methods for assessing the acceptability of flaws in metallic structures. British Standard Institution, London, 2005.
8. Ainsworth, R A. The use of failure assessment diagram for initiation and propagation of defects at high temperatures. *Fatigue Fract. Eng. Mater. Struct.*, 1993, **16**(10), 1091-108. doi: 10.1111/j.1460-2695.1993.tb00080.x
9. Cravero, Sabastian & Ruggeiri, Claudio. Structural integrity analysis of axially cracked pipelines using conventional and constraint modified failure assessment diagrams. *Int. J. Pres. Vessel Piping*, 2006, **83**(8), 607-17. doi: 10.1016/j.ijpvp.2006.04.004

10. Budden, P.J. & Ainsworth. R.A. The shape of a strain-based failure assessment diagram. *Int. J. Pres. Vessel Piping*, 2012, **89**, 56-66. doi: 10.1016/j.ijpvp.2011.09.004
11. ASTM Standard E-399. Standard Test method for plane-strain fracture toughness of metallic materials. *Am. Soc. Test. Mater.*, 1997, Section A4, 16-19.
12. ASTM Standard E-1820. Standard test method for measurement of fracture toughness. *Am. Soc. Test. Mater.*, 2001, Section A2, 14-18.
13. Malakondaiah, G.; Saxena,Vikas Kumar & Prasad, N. Eswara. Fracture toughness evaluation. *Trans. Ind. Inst. Metals*, 1996, **49**(5), 697-23.
14. Saxena, Vikas Kumar; Srinivas, M. & Malakondaiah, G. Computerize single specimen technique to evaluate elastic-plastic fracture toughness J_{IC}. *Trans. Ind. Inst. Met.* 1989, **42**(6),507
15. Rice, J.R. A path independent integral and the approximate analysis of strain concentration by notches and cracks. *J. Appl. Mech.*, 1968, **35**, 379-86. doi: 10.1115/1.3601206
16. ASTM Standard E-647. Standard test method for measurement of fatigue crack growth rates. *Am. Soc. Test. Mater.*, 2001, Section **A1**, 10-14.

CONTRIBUTORS

Mr Shahnawaz Ahmad did his BTech (Mechanical Engineering) from Aligarh Muslim Univerity, Aligarh. MTech (Solid Mechanics and Design) from IIT Kanpur. Presently working as Scientist 'D', Mechanical Behaviour Group at Defence Metallurgical Research Laboratory, Hyderabad. His current areas of interest are : Structural Integrity analysis and life prediction technologies of aero-engine components.

Dr Vikas Kumar has received BE from University of Roorkee and MTech from IIT, Kanpur, in Metallurgical Engineering in 1980 and 1982, respectively. He received PhD in Metallurgical Engineering from IIT, Madras in 1995. Presently working as Scientist 'H' and Head, Mechanical Behaviour Group at Defence Metallurgical Research Laboratory, Hyderabad. His current areas of interest are : Microstructure-property-performance correlation, thermo-mechanical fatigue, fracture and damage mechanics, life prediction technologies, and structure integrity analysis.