Peacemaker: Fracture Assessment of a 155mm Cannon Barrel

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by

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Conclusion

A single crack 30 mm or deeper which is 75 mm long is sufficient to fracture a typical 155 mm cannon barrel with a pressure at or above two-thirds (206 MPa - 30 ksi) of the maximum operating pressure (310 MPa - 45 ksi). Longer and deeper flaws reduce the critical pressure required to initiate fracture. For the monolithic barrel design considered in this work, the postulated 30 mm deep by 75 mm long crack should propagate through the entire wall and, depending upon the new "fractured" geometry, may propagate axially down the cannon barrel. Numerical analyses conducted with straight through-thickness crack fronts propagated axially at pressures below the maximum operating pressure while those with curved crack fronts required pressures in excess of the working pressures to extend axially. (Experiments¹ on actual 155 mm barrels with flaws similar to the one generated by the tested shape charge show appreciable axial crack extension at approximately equivalent pressures.) In either case, a through-thickness "hole" will be formed in the barrel's side and a reduction in firing pressure should result. Finally, debris deposited within the barrel can greatly assist the fracture process, especially at lower operating pressures.

Overall, a single deep and long interior crack appears the most effective way to fracture a cannon barrel. Unless clustered very closely together, multiple "shallow" cracks require higher pressures to fracture than does a single deep crack. Flaws introduced on the barrel's exterior are less efficient since no crack-face pressures exist and the overall stresses on the barrels' exterior are much lower than on its interior. Thus, very very deep exterior cracks would be required to fail the barrel from internal pressure.

Summary of Fracture Analyses

2-D Analyses

Several 2-dimensional and 3-dimensional fracture analyses of a typical, but damaged, 155 mm gun barrel were performed. The plane strain 2-D models considered a cross section of the barrel with a single 12.7 mm radial crack. (The crack faces were normal to the θ direction.) The inside bore and the crack faces were pressurized. The elasto-plastic analyses indicate that pressures slightly below 310 MPa (45 ksi), the maximum operating pressure of a typical 155 mm cannon, result in a K , stress intensity factor, that exceeds K_{Ic} , the material's fracture toughness. (See the section entitled "Material and Cannon Specifications" for details regarding the material properties and geometry used.) At this pressure, the 2-D model indicates that cracks of this size would propagate in the radial direction. Furthermore, the full field results showed very little plastic deformation, and thus small scale yielding (SSY) conditions "exist." Based upon the 2-D results for a 12.7 mm crack, $K_{Ic} = 165 \text{ MPa}\sqrt{m}$ ($150 \text{ ksi}\sqrt{in}$), and assuming SSY conditions exist, the critical internal gun barrel pressure, σ_c , required to cause through thickness fracture is

$$\sigma_c \approx \frac{34.9}{\sqrt{a}} \text{ MPa} \quad \left(\text{or} \quad \approx \frac{31.8}{\sqrt{a}} \text{ ksi} \right), \quad (1)$$

where the crack length a is expressed in m (or in).

In this configuration the crack-face pressure is responsible for approximately half of the resultant K . Thus, if pressure could not reach the crack face, say debris blocked the air flow, the barrel would not fracture.

Although the 2-D calculations show that moderate pressures cause fracture with realistically achievable crack lengths, they assume that the crack and the barrel are infinitely long. Actually, the cracks may only be 75 to 100 mm (3 to 4 in) long and 3-D effects become important. In order to address this short coming, a series of 3-D calculations were performed.

3-D Analyses

3-D analyses of the postulated crack geometry and the surrounding barrel region were performed. First, a rectangular 12.7 mm (0.5 in) deep crack, 101.6 mm (4 in) long was

modeled along with the surrounding barrel region. Symmetry was assumed to exist in a plane normal to the crack face as well as in a plane normal to the semi-major axis of the crack, i.e., quarter symmetry was presumed. The orientation of the crack was identical to that used in the 2-D configurations. An internal pressure of 310 MPa produces K -values in excess of K_{Ic} over the central 63.5 mm section of the 101.6 mm long radial crack front. Thus, fracture in the radial direction appears likely and should follow approximately the critical pressure/crack-length relationship given by equation (1). K -values at the top and bottom of the crack, along the 12.7 mm face, were below K_{Ic} . Thus, axial crack propagation is not anticipated based upon the original crack geometry.

The second configuration examined considered a 76.2 mm (3 in) long, through-thickness crack. (The crack went all the way through the wall.) Although the interior bore was fully pressurized, crack-face pressures were applied only over the region corresponding to the originally postulated 12.7 in deep crack. The K -values under this scenario were all (almost) at or exceeded K_{Ic} indicating that axial crack propagation would result across the entire crack face. Increasing the size of the pressurized crack-face region increases the resultant K -values and enhances the likelihood of axial crack propagation.

Based upon these 3-D results and the assumptions associated with equation (1), the critical internal gun barrel pressure, σ_z , required to cause axial fracture across the entire crack front is given by

$$\sigma_z \approx \frac{60.5}{\sqrt{a_z}} \text{MPa} \quad \left(\text{or} \quad \approx \frac{55.1}{\sqrt{a_z}} \text{ksi} \right), \quad (2)$$

where the axial crack length a_z is expressed in *m* (or *in*). (Note, the entire crack length is $2a_z$.) This equation assumes that 12.7 mm of the crack face is pressurized, and thus, is conservative if the original crack depth is deeper than 12.7 mm.

Finally, an analysis of an actual, shape charge induced, crack front was modeled. Figure 1 shows $\|K\|/K_{Ic}$ (where $\|K\|$ is the magnitude of K) as a function of station number when the interior gas pressure is 310 MPa. The figure also indicates the crack depth, normal to the interior bore, of the approximately 114.3 mm long crack at each monitoring station. (Unfortunately, the station numbers are not equally spaced along the crack front.) Neglecting

station points where sharp "corners" exist in the crack front profile i.e. station numbers 9, 17, 19, 20, and 24, nearly the entire crack front has $\|K\|$ -values in excess of K_{Ic} at 310 MPa. Scaling these results, the critical pressure to start uncontrollable crack propagation is about 210 MPa and will occur around station 14. Here the crack is approximately 2 mm deep, and growth will occur primarily in the radial direction. Using the maximum crack depth of 35 mm, the 2-D based equation (1) predicts that crack growth would occur at $\sigma_c \approx 190$ MPa which is consistent with these 3-D findings. However, the 3-D results indicate that crack advancement occurs in the shallower crack region first. Using equation (2) and $a = 0.057$ m, $\sigma_z \approx 150$ MPa which is about 35% lower than these results would indicate.

The K -values of the actual crack front geometry are not as high as the previous 2-D and 3-D analyses would suggest. This may be due, in part, to insufficient mesh refinement. However, the curved crack front alters the local direction of crack advancement. This forces the crack growth to occur in both the axial and radial directions and thus, in this case, reduces the local driving force as measured by $\|K\|$. Nonetheless, radial crack growth at moderate pressures appears favorable. Whether or not axial crack growth will accompany the radial growth depends upon the deformed crack front geometry and whether the crack faces remain pressurized.

Experiments on actual 120 and 155 mm barrels by Underwood¹ showed that for defects similar to the one just analyzed appreciable axial crack growth accompanied the through thickness fracture event. In his experiments in which the gun barrel was hydraulically pressurized, crack lengths increased axially by as much as a factor of seven.

Effect of Debris

The consequence of debris "jamming" the artillery shell inside the gun barrel was examined. By idealizing both the barrel and artillery shell as infinite cylinders, simple 2-D closed-form equations were developed. Based upon literature provided by R. Kuklo, the outside of the artillery shell and the barrel's "land" (the interior bore of the gun) have a

¹Streit, R., 1993, Private communications with J. H. Underwood - US Army Armament Research, Development and Engineering Center.

Material	Yield Strength (<i>ksi</i>)	Fracture Toughness (<i>ksi</i> $\sqrt{in}$)
4330	160 - 180	140 - 150
A723 (a)	190	135
A723 (b)	160 - 170	140 - 165

Table 1: Mechanical properties for cannon steels.

minimum of approximately 0.008 *in* diametrical clearance when cold. Accounting for the clearance and assuming a uniform 2 *mm* distribution of debris within the barrel, the equivalent pressure generated by "wedging" a shell inside the barrel would be between 620 and 1700 *MPa* (90 and 250 *ksi*), depending upon the thickness of the artillery shell walls. (The lower value assumes a 12.7 *mm* thick shell wall while the upper value assumes a solid steel shell.) Based upon previous findings, the lower effective pressure would be sufficient to fracture the barrel radially when cracks 12.7 *in* deep or deeper are present.

Material and Cannon Specifications

According to military specification MIL-S-46119 (March 23, 1967), tubular cannon parts "are" manufactured from V-modified 4330 steel (oil quenched). More recent data from the US Army Armament Research, Development and Engineering Center indicates that modern cannon barrels are made from ASTM A723 steel. *Table 1* summarizes the mechanical properties of both the V-4330 and A723 steels. It appears that modern designers favor the tougher A723(b) steel that has a slightly lower yield strength¹.

The physical dimensions of the cannon barrel vary depending upon the specific design. Typical inside to outside diameter ratios for a 120 and a 155 *mm* gun are 2.25 and 1.79, respectively. In this study the outside diameter for the 155 *mm* cannon is assumed to be 284.5 *mm*.

Post Processor: 3-D *J*-Integral

In order to perform the 3-D fracture analyses, a 3-D *J*-Integral routine was written. The post processor is "shoe-horned" into B. Maker's TDBD program. The features of the 3-D

routine are not as complex as those continued in NIKE2D, but they are sufficient for this work. It extracts the J -values along the crack front for multiple rings. Post processor tests on several classical problems achieved J 's within 1% of their analytical values.

Stress Intensity Factor

Figure 1: The normalized magnitude of the stress intensity factor K vs. monitoring station number for an actual, shape charged induced, flaw. The barrel is pressurized to 310 MPa. Crack depth normal to the surface at each station is also shown.