Analysis of Excalibur/M284 Muzzle Brake Interference Issues

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Abstract:

In late 2007, two problems concerning the 155 mm Excalibur round being fired through the M284 muzzle brake were presented to Benét Laboratories. The first of these problems was a base failure during lot testing in which the threads connecting the base to the rest of the projectile failed. This only occurred once. The second of these problems was that the obturating band of the Excalibur round contacts the M284 muzzle brake on reportedly every shot. Benét's goal was to determine the effect these issues would have on the integrity and service life of the muzzle brake and other gun components. Through the use of finite element modeling and a fatigue and fracture analysis, it was determined that the obturating band contact is not strong enough to cause the brake to be damaged or experience a noticeably shorter life. The likelihood of the thread failure causing the base to become completely removed in the brake region was determined by the customer to be negligible, even if the thread failure occurred in bore. These results assume that the problem was accurately described to Benét and that no adverse conditions occur beyond what was described.

Background and Scope:

During lot testing of the 155mm Excalibur round in Sweden, one round failure was observed. This was a thread failure which caused the base to separate from the rest of the round. The base of the Excalibur round contains the fins and the base bleed components, among other items, which are all contained underneath a hood which is extracted after shot exit. This failure occurred on one of the two rounds tested from the lot of approximately 60 rounds. Therefore, 50% of the tested rounds failed for that lot. But, this failure mode had never occurred previously and has not occurred since. The cause of this failure is unknown, and therefore it cannot be readily repeated and tested. Because of this failure, Benét Laboratories was notified of another problem that is much more frequent during firing of the Excalibur round. When fired with the M284 muzzle brake, the obturating band is known to contact the first baffle of the brake on nearly every shot. This is known because of the PEEK (polyetheretherketone) residue left behind on the brake. There is never any evidence of metal to metal contact, only PEEK to metal contact from the obturating band. The aluminum lip directly behind the obturating band is often damaged as well.

Scope:

The concerns presented to Benét were twofold. First, it was necessary to determine if this initial impact of the obturating band on the first baffle could cause the base thread failure, and if this thread failure occurred, could the base separate before leaving the brake and damage the brake. Second, it was necessary to determine the effects of the first impact on the brake, such as its contribution to fatigue, on the threaded connection between the brake and the tube, and any other potentially detrimental effects.

Analysis Setup:

Benét performed a dynamic structural analysis using the information made available regarding the conditions occurring during muzzle exit. Several scenarios were considered due to the unknown nature of the exact motion of the projectile as it exits the muzzle of the gun tube and enters the muzzle brake region. The given initial conditions of motion were a muzzle velocity of 520 meters per second (m/s), a tip off rate of 7 radians per second (rad/s), and a spin rate of 14 Hertz (Hz). The overall length of the muzzle brake is 846 mm and the length of the projectile is approximately 967 mm, meaning the projectile would have a portion of itself inside the brake region for 3.5 milliseconds (ms) and would spin a total of 18°. Since this number is small, it was assumed that the spin rate would not affect the results of the impact and the situation could be modeled as a half model with symmetry boundary conditions rather than a full model incorporating spin. The other boundary condition in this model consisted of constraining the rear most face of the muzzle brake from both translation and rotation, providing a conservative starting point for gathering results. The material properties were gathered from several sources, including published data, in-house test results, and a finite element model which was provided by the Excalibur team. This analysis and the model from the Excalibur team were performed using the finite element analysis (FEA) software package Abaqus. The geometry and associated mesh are shown in Figure 1.

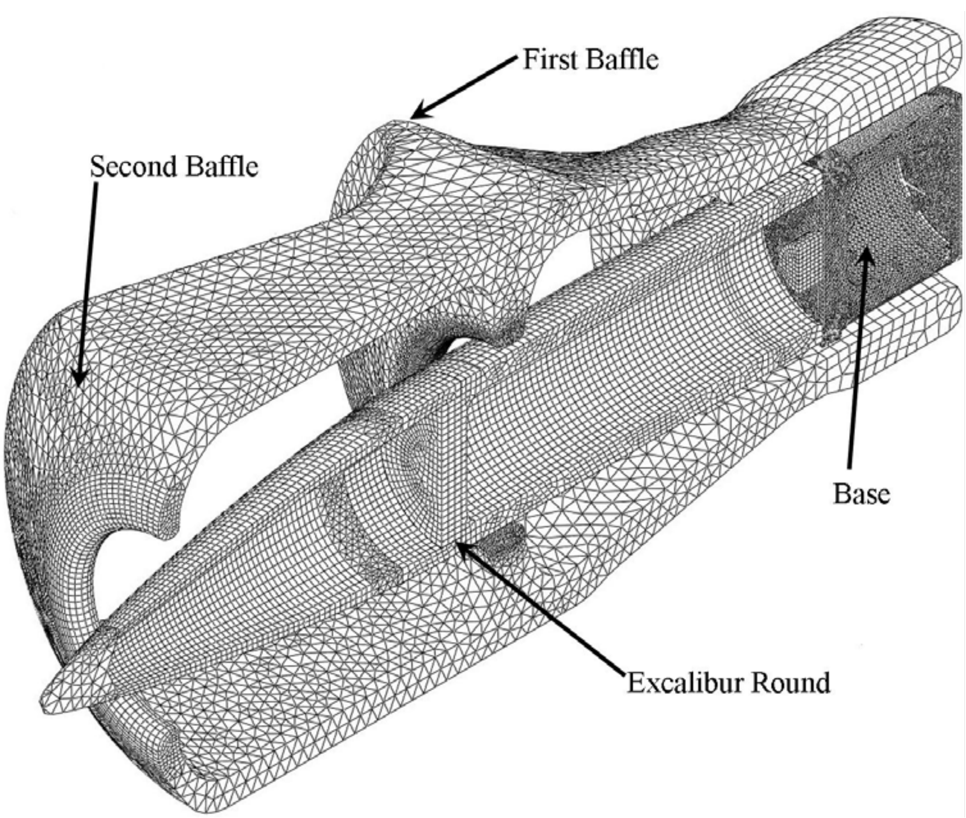

Figure 1. Geometry and mesh for ABAQUS FEA model

Although brick elements were preferred throughout the model, they were not practical to use in every region. Therefore, constant stress linear tetrahedrons (C3D4) were used where bricks were not practical and where bricks were unnecessary due to the lack of major expected stress gradients. The brick elements used were linear first order reduced integration elements with hourglass control (C3D8R). In the areas where impact occurred and where much of the stress and strain activity was expected, closely spaced brick elements were used. These areas were modeled with the ability to erode away and be removed from the model if the model predicted them to fail based on the given material properties. This was done by using the *Contact Inclusions keyword and manually creating a surface that would include all of the element faces that might be exposed as other elements were eroded away.

The most difficult portion of this situation to model was the connection between the base and the rest of the projectile. The threads were not modeled individually, and therefore an alternative method was necessary to determine if the threads would fail. A worst case scenario would consist of there being no connection between the base and the projectile body. They would initially travel at the same velocity, but any force imparted on the base would immediately cause its path to be diverted from that of the projectile. This method was chosen as a conservative approach to see what the worst case results would be if the thread had failed in bore. An explicit dynamic model was used to speed solution time compared to an implicit model, and the time steps were chosen automatically by the program. Data was recorded every 600 microseconds until the obturator band and the first baffle were about to contact, then data was recorded every 100 microseconds shortly before and shortly after the impact, and finally data was recorded every 600 microseconds again until the projectile had left the muzzle brake region.

Results:

Several initial iterations were attempted in order to replicate the impact as described, with the obturating band impacting the first baffle of the brake with enough force to deposit PEEK onto the brake while avoiding any metal to metal contact. The major portions that needed to be simulated were the expansion of the obturating band and the damage to the aluminum lip behind the obturating band. To simplify the modeling process, the geometry of the band was set up to be initially expanded to the point where it was as large as possible while still contacting the aluminum lip. The assumption was that when the band impacted the baffle, the force would transfer through the band and damage the lip. This provided the initial geometry, and the model was run with the initial conditions and boundary conditions given previously.

Because these results of the model matched the described phenomena closely, the model was extended to run beyond solely the impact time to determine if thread failure would occur, if the base could fully separate while it was inside the muzzle brake region, and if anything else might happen in that region. Although the model did show the base beginning to separate from the projectile body within the brake region, the difference was not enough to cause any additional impacts with the muzzle brake. The actual maximum separation distance was 0.2 mm, or approximately 0.008 inches between the base of the projectile and the main body of the projectile, and occurred on the side where the impact took place. This amount of separation occurred when the projectile had already moved beyond the muzzle brake region. If there were any sort of connection between the base and the rest of the projectile when the projectile left the tube bore, this number would have been even smaller because a good portion of the energy would have been absorbed in breaking the connection between the two parts instead of being completely changed into relative motion. The likelihood that the impact of the obturator band on the muzzle brake would cause base failure is minimal, and the one base failure that did occur may have been caused by some sort of manufacturing defect.

Figure 2 shows the results at the moment in time where the stress in the brake due to the impact was the highest. The stresses in the plot are in units of Pascals.

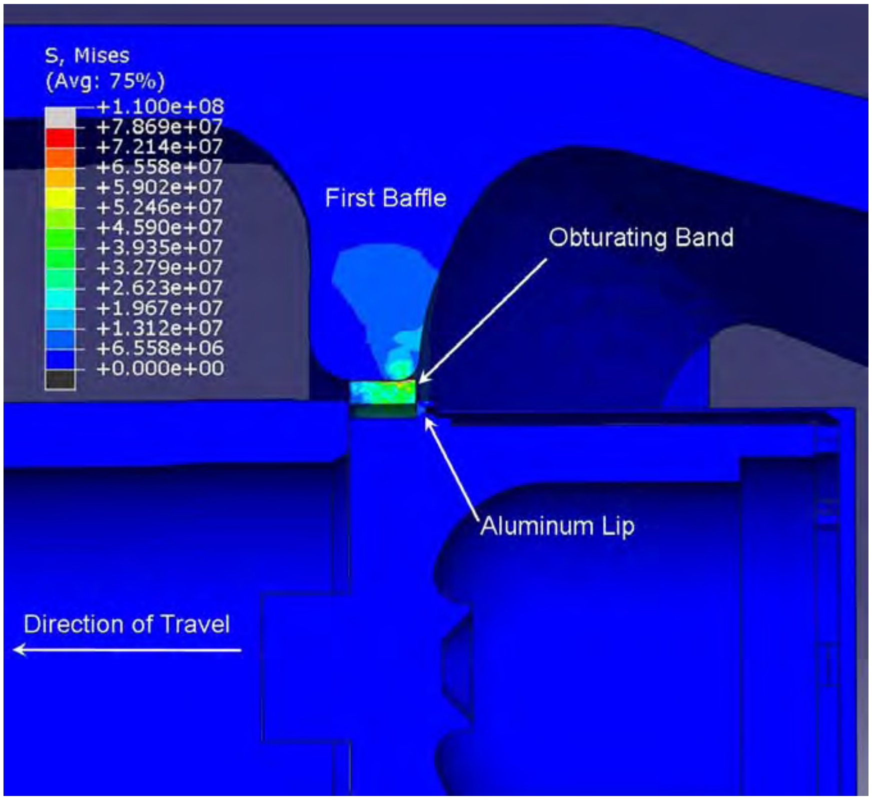

Figure 2. Maximum Mises stresses during impact (Pa)

The total additional stress imparted on the first baffle of the brake due to the impact was 15 ksi. With the yield strength of the material being 160 ksi and the peak principal stress in the brake due to other factors being 53 ksi (Troiano, 2003), this should not cause any additional problems in the survivability of the brake in terms of the material yielding. Also, the stress was localized in the region of impact and did not spread to the rest of the brake at any significant levels. Because of this, the likelihood of the impact damaging other portions of the gun system such as the threaded connection between the gun tube and the brake is minimal. As some systems with similar configuration muzzle brakes are towed systems where a tow bracket with a lunette attaches to the muzzle brake, the stresses on these threads due to the towing would most likely be higher than the stresses due to this impact.

Fatigue and fracture were also looked at as being possible areas of concern with this impact. The areas of concern in terms of fatigue and fracture in this brake are in the corners where the main structure of the brakes curve down into the baffles (Fujczak & Kapp, 1994). This is where the cracks initiate and where fatigue failure would occur. The most critical surface was the inner surface of the first baffle. In order to determine how much the additional stresses affected the results, the method presented in the Fujczak & Kapp paper was followed, with the additional stresses from the proper locations added to the stresses from the original study. The maximum principal stress on the top of the web of the rear baffle due to the obturator impact was 459 psi. The minimum principal stress on the bottom of the web was -725 psi. These values were taken directly from the FEA model with the assumption that the stress results are linear, as plasticity does not occur, and superposition would apply. Then, proceeding through this analysis, along with following the procedure shown in Newman & Raju, 1979, to determine the stress intensity factor, the fatigue life of the brake at this location was reduced by approximately 1%, with no effect on critical crack size. A 1% decrease in fatigue life is essentially negligible. Figure 3 shows the crack growth rate and the stress intensity factor from this analysis plotted versus the number of cycles, which is the number of rounds fired.

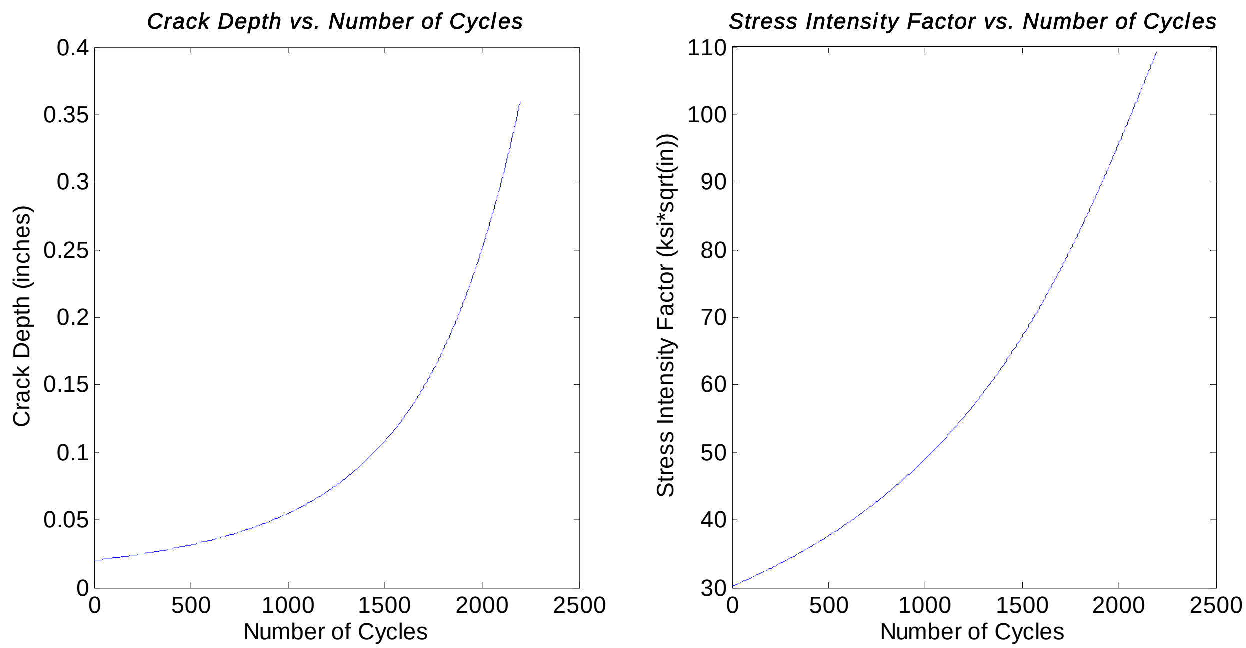

Figure 3. Crack depth and stress intensity factor vs. number of cycles

This analysis was performed assuming a critical crack length of 0.36 inches and an initial crack size of 0.02”. These numbers are from Fujczak & Kapp, 1994, and were repeated in Troiano, 2003. Because the crack size was used to determine when the brake would fail due to fatigue instead of the stress intensity factor, it was imperative to check and make sure the stress intensity factor did not exceed the fracture toughness of the material. Fujczak & Kapp reported that the measured fracture toughness of the material was greater than 120 ksi√in. The plot shows that the stress intensity factor at a crack size of 0.36” was approximately 110 ksi√in. Therefore, it is possible that the crack would grow even further before sudden fracture and therefore have a longer life than predicted, minimizing the 1% reduction in life due to the impact.

The results of this model showed no reason for concern in terms of the effect on the projectile or the immediate effects on the brake. There was no metal yielding and the impact was not located near the crack initiation regions. The 15 ksi maximum stress was not enough to cause fatigue or fracture problems, and the very low stresses in the crack initiation regions were low enough to almost imperceptibly decrease the fatigue life. The obturating band was completely destroyed in the area of impact, but since it was designed to be discarded after leaving the tube, this is inconsequential to its performance. The model showed that the aluminum lip underwent plastic deformation and failed in the contact region, but was not damaged to quite the same level as observed in the firing tests. This could be due to the lack of spin in the model preventing the impact from affecting as much of the aluminum lip as it otherwise could have affected. This is also inconsequential to the performance of the projectile as the aluminum lip has already finished serving its purpose when the damage occurs. These results all assume that the impact is never any worse that was initially reported.

Conclusion:

This model, developed at Benét Laboratories, shows what is expected to happen in a typical shot of the Excalibur round through the M284 muzzle brake. To determine the effects of a worst case shot, the initial conditions were modified to achieve the most forceful possible impact that could take place without causing metal to metal contact. This worst case impact did not cause the base to become completely disconnected from the projectile within the muzzle brake region. The model shows that the base should not undergo a more forceful collision with the second baffle. As a result of this analysis, it is recommended that cannon that fire the Excalibur round be visually examined for evidence of metal to metal contact or deformation caused by an impact from the projectile. The cracks and service life issues can be treated as they have been before this problem was discovered.

The results of the analysis suggest that there is no detrimental damage to the M284 muzzle brake from the type of impact described and modeled under this effort. If the conditions surrounding the firing change and move outside of these boundaries, it is unknown what the results will be and it is recommended that this analysis be revisited in such a case. The study did not attempt to determine the cause of the impact. The objective was only to determine what the results of the impact would be on the integrity of the cannon system. Therefore, any additional impact conditions would need to be studied in further detail.

Acknowledgements:

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