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The Effect of Mortar Diameter on the Burst Height of Three-Inch Spherical Aerial Shells

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Background

A while ago, a small fireworks display company called seeking information about the effect of mortar internal diameter on the burst height expected to be achieved by aerial shells fired from them. It seems the company had received a large quantity of three-inch, high-density polyethylene (HDPE) pipe that they had cut into 18-inch lengths for mortars (including 1.5-inch thick plugs) before having checked the pipe's internal diameter. When it was checked, the HDPE pipe was found to have an internal diameter of 3.21 inches (i.e., it was significantly oversize). Because it was close to the July 4th holiday season, there was not sufficient time to replace the pipe. Accordingly, the question was, could these mortars be safely used?

Of course, one problem with mortar diameter being greater than expected is that this results in greater clearance between the shell and mortar, through which more than the usual amount of burning lift gas will escape. Typically, the gap between shell and mortar amounts to about 20 percent of the cross-sectional area of the mortar. (For example, with a 2.7-inch diameter shell and a 3.0-inch diameter mortar, the gap amounts to 19 percent of the cross-sectional area of the mortar.) However, for these oversized mortars, the gap was about 30 percent of the cross-sectional area, thus reducing the normal lift pressure and causing the shells to be propelled to less than full height.

Generally, shells can be propelled to a greater height by lengthening the mortar. This is because aerial shells normally exit the mortar while there is still significant lift pressure in the mortar. Accordingly, if a mortar is lengthened, some of this normally wasted lift energy will be used to increase the muzzle velocity of (and thus the height reached by) the exiting aerial shell. In this case, had the pipe not already been cut into short lengths, the effect of an oversize diameter might have been compensated for, simply by making the mortars somewhat longer. Since this was not an option, the question remained, would these mortars propel their aerial shells to a safe height?

However, there is another issue not addressed in the initial question about shells attaining a safe height. For the most part, all three-inch HDPE pipe is extruded with the same outside diameter, 3.50 inches.[a] Accordingly, as a consequence of this pipe having an oversize inner diameter, its wall thickness was less than expected. In this case, the wall thickness was approximately 0.15 inch as opposed to the expected thickness of approximately 0.25 inch. Thus, an additional question was, is this pipe sufficiently strong to be safely used. Fortunately, a previous study (unpublished) of the effective burst strength of HDPE mortars had demonstrated that even these thin-walled, three-inch mortars were still amply strong to be safely used.

Discussion

For the most part, the effect of mortar diameter has received relatively little attention in the literature. Some of the writings of T. Shimizu address the subject to some extent, and he has suggested a mathematical model incorporating the effect of shell-to-mortar clearance,[1] providing the clearance is not too great. However, neither Shimizu nor anyone else we are aware of has provided quantitative data based on field measurements. Because time was extremely short before the display company needed to use the mortars, only the briefest of investigations could initially be undertaken. A series of 12 shell firings, six from the oversized mortar and six from a 3.00-inch ID mortar, was conducted. The burst height of these shells was determined by measuring the amount of time elapsing between the burst of the shell (as determined optically) and the arrival of the sound of the burst.[b] Unfortunately, only a limited number of shells were available at the time for testing.

The only manufacturer for which there were a sufficient number of three-inch shells was Horse Brand, and even those were a variety of shell types. Nonetheless, the testing was performed while trying to match pairs of shells (for firing from both size mortars) as best as one could. The results were that the average burst height using the normal 3-inch mortar was 345 feet, while that for the oversized mortar was 277 feet, with both data sets producing a fairly wide range of burst heights. The difference corresponds to approximately a 14% reduction of burst height for these oversized mortars as compared with those achieved using 3.00-inch mortars.[c]

More than a year later, after performing some tests as part of another project, some of the 3-inch shells used in these later tests remained unused. These were Thunderbird, Color Peony-White (TBA-106) shells having an average mass of 136 g, an average diameter of 2.72 inches, and an average of 37 g of lift charge (apparently 4FA granulation). Five test shells were fired from each of three mortars with different internal diameters (2.93, 3.02 and 3.21-inches). Approximately 10 minutes elapsed between each use of a mortar, to allow time for the mortar to cool before its next firing. The average heights of the shell bursts were determined as described above[b] and found to be 530, 490 and 460 feet for the three mortar diameters, respectively.[c] If the burst height from the 3.02-inch mortar is defined as 100%, the mortar with the tight fit produced a burst height increase of approximately 8% and the mortar with the loose fit produced a reduction in burst height of approximately 6%.

In each case, the one-sigma coefficient of variation[d] was about 10% (approximately 50 feet) and the standard error[e] was about 5% (approximately 25 feet). Also, had the shells been fired at about 1000 feet of elevation above sea level, based on an increase in air density, the burst heights would have been reduced by roughly 50 feet.[f]

While the burst heights may be unexpectedly high for those using the 100 feet per shell-inch rule of thumb, this rule of thumb was found to under estimate actual burst heights.[5] Also, it must be recalled that the testing was performed at nearly a mile above sea level with a corresponding reduction in air density. Further, the test shells were a little larger (tighter fitting) than normal, and they had greater lift mass than is typical for 3-inch spherical aerial shells. Finally, the mortar was about 10% longer than the 15 inches recommended by the NFPA.[6] Accordingly, considering everything, it is thought that the measured burst heights are approximately correct.

The results from these two brief tests are summarized in the table below. Accordingly, it is concluded that the effect of using the oversized mortar is a reduction in burst height of approximately 10%. However, it must be considered that the statistical uncertainty in the combined measurements is a little more than 3%. Thus the effect on burst height resulting from the use of the oversized mortar could easily be anywhere in the range from about 5 to 15%. Certainly it would have been preferred to have results with better statistical precision; nonetheless it is clear that there was not an overwhelming decrease in the burst height of the shells fired from the oversized mortar in this instance. While this is not the preferred situation, neither does it represent a substantial safety concern. Also, in this instance, the reduction in burst height is small enough that it could have easily be compensated for by a modest increase in mortar length.[g]

Mortar Diameter	Percent Change in Burst Height(a)		
	Test 1	Test 2	Average
3.21 in.	–14	–6	–10%
2.93 in.	—	+8	—

a) The change in burst height is compared with shells fired from a 3.02-inch mortar.

It is hoped that these brief studies and this article have provided some useful (and perhaps interesting) information on the effect of mortar diameter on the burst height achieved by small caliber aerial shells.

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Notes

a) Typically, as HDPE pipe is extruded, it is drawn through a "vacuum sizer" which literally sucks (expands) the still pliable pipe up to the size of the vacuum sizer. The vacuum sizer is generally water-cooled and of sufficient length to maintain the pipe's diameter until the pipe has cooled sufficiently, so the pipe will retain the correct diameter.

b) If desired, see references 2 and 3 for discussions of two slightly different methods using the delay in arrival of the sound of the explosion to determine the distance to the explosion.

c) Testing was conducted in western Colorado at an altitude of 4600 feet above sea level. The reduced air density at this elevation results in lower drag forces, such that aerial shells travel faster for longer (i.e., shells will have greater burst heights) than when fired nearer sea level.

d) The coefficient of variation is the standard deviation expressed as the percent of the mean.

e) The standard error in this case is expressed as a percentage and is the coefficient of variation divided by the square root of the number of measurements.

f) Based on the use of a computer ballistics model for fireworks aerial shells.[4]

g) For example, for the same shells used in this study, fired from a minimum length mortar, 15 inches above the plug, the burst height can be increased by about 10% by simply increasing the mortar length to about 19 inches.[7] However, the reduced lift pressure would require a mortar length in excess of 19 inches to compensate fully.

References

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