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Mortar Plug and Recoil Problems

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(Note that this article contains a number of explanatory notes at its end. These are identified in the text as superscript letters in square brackets. While these notes may be of interest to some readers, they are ancillary in nature and readers may wish to ignore them until and unless they want further information.)

As is so often the case, this is an instance where one might take a useful lesson from someone else's unfortunate experience. This article recounts a relatively minor incident experienced by a display company, but one that could have been of significantly greater consequence.[a] The purpose of the article is to use this incident as the basis for discussing potential problems regarding mortar plug attachment and mortar recoil forces, which others in the industry may benefit from considering in greater detail.

As part of a firework display, a volley of 4-inch double-break spherical aerial shells[b] were to be fired from three racks positioned side by side. The shells were loaded into the company's normal mortars in their standard racks. These mortars and racks had been successfully used many times previously to fire single-break spherical shells of the same diameter. However, on this occasion, heavier and more powerfully-lifted double-break shells were being fired from the relatively weak and flexible deck of an old wooden barge. On this occasion, upon firing the shells, the mortars recoiled with enough collective force for the racks to break through the wooden deck of the barge (see Figures 1 and 2). In addition, most of the mortars blew (lost) their plugs (see Figure 3).

Where the mortar plug attachment in this incident was sufficient for the firing of typical shells in the past, it was not sufficient for the shells on this occasion when fired from the barge deck. It can reasonably be concluded that two factors combined to produce the mortar plug failure, one fairly obvious and one not so obvious. The fairly obvious factor is that the internal mortar pressures for these double-break spherical shells are expected to have been roughly double that for typi-

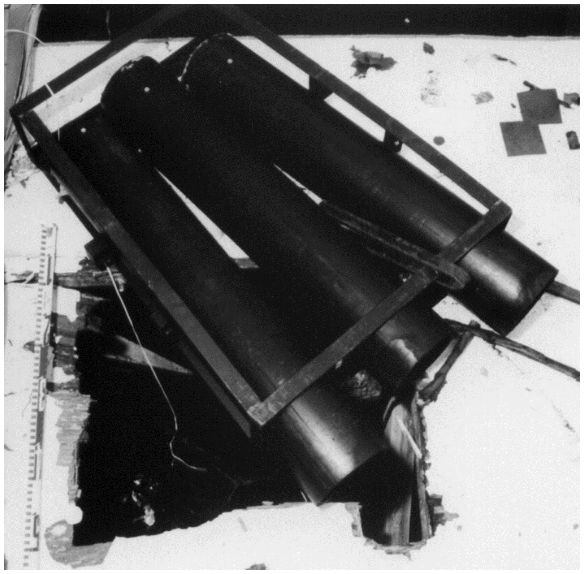

Figure 1. A photograph of deck of the wooden barge, with one of the three mortar racks partially covering the hole in the deck.

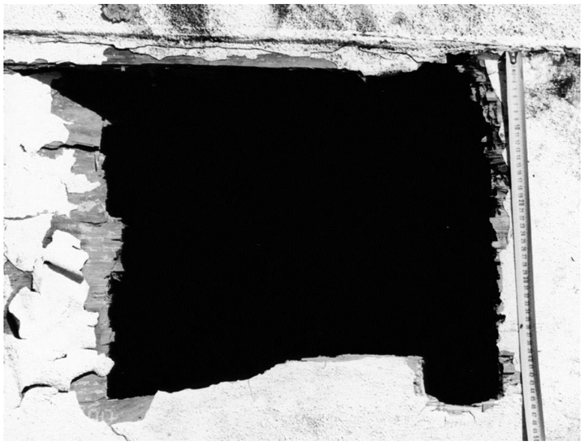

Figure 2. A photograph of the approximately 18-inch square hole in the deck of the wooden barge where the three mortar racks had broken completely through.

Figure 3. A photograph of the bottom of one of the mortar racks in which two of the three mortars had completely lost their plugs.

cal single-break spherical shells,[c] thus requiring a mortar plug attachment strength that was also approximately double.

The not so obvious factor contributing to the mortar plug attachment problem is the role played by the relatively weak and flexible barge deck. When firing a mortar that has been placed in firm contact with a very strong and unyielding supporting surface (like pavement or firmly compacted ground), it can be considered that the attachment between the plug and mortar is not so much to keep the plug from blowing downward out of the mortar, but rather to keep the mortar tube from lifting upward off from the plug. That is to say, there is an upward force on the bottom of the plug produced by the very strong and unyielding support surface below the mortar plug that approximately balances the downward force on the top of the plug produced by the high pressure lift gas inside the mortar. Figure 4 is an attempt to illustrate this, where it can be seen that the forces acting against the top and bottom of the mortar plug are approximately balanced.[d] Because of this approximate balance, there will be essentially no tendency for movement of the plug.[e]

There is, however, another much smaller upward force that acts to lift the mortar up from the plug. This upward force acting on the mortar is primarily a result of frictional forces produced by the upward flow of lift gas escaping from around the aerial shell. Thus, in the case of firing the mortar from a very strong and unyielding supporting surface, for the most part the attachment of the mortar plug need only be sufficiently strong to safely counter this relatively small upward force on the mortar.[f]

Now consider the situation where the same mortar and shell are fired from a comparatively weak and flexible support surface. In this situation, when the shell fires, the downward force from the lift gas on the top of the mortar plug is not balanced by an upward force from the support surface. Thus the mortar plug begins to move downward. As a result of the attachment between the plug and mortar tube, the downward movement of the plug acts to pull the mortar tube down. Because the mortar tube has mass, a force is developed as a result of the tube's inertial re-

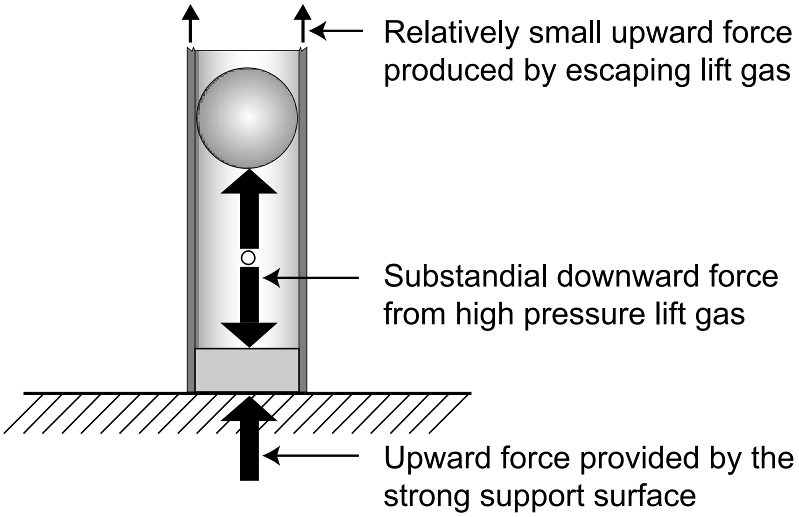

Figure 4. An illustration of the nearly balanced forces acting on the mortar plug that is resting on a very strong and unyielding supporting surface.

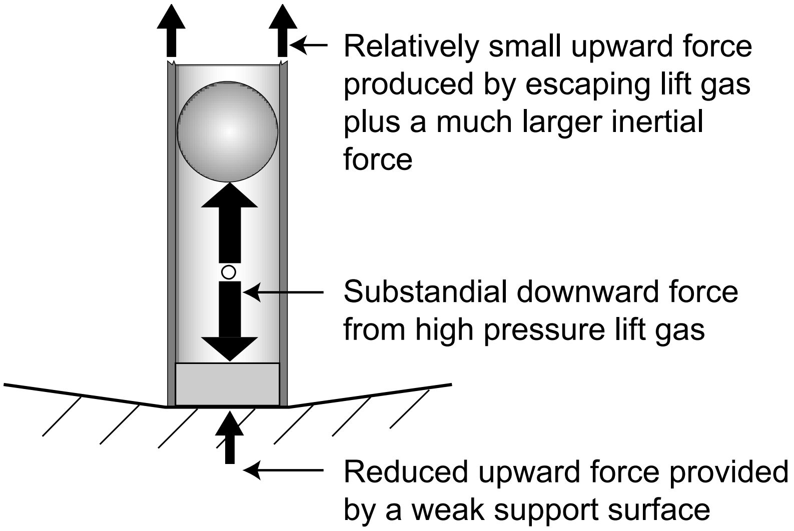

Figure 5. An illustration of the unbalanced forces acting on the mortar plug that is resting on a comparatively weak and flexible supporting surface.

sistance to its sudden downward movement. In this case the attachment of the mortar plug needs to not only counter the relatively small upward force from escaping lift gas trying to lift the mortar up from the plug (as was discussed above), the attachment also needs to be strong enough to counter a much larger inertial force developed due to the sudden downward movement of the mortar tube. Figure 5 is an attempt to illustrate this.

The length, strength and number of nails securing the mortar plugs used in the incident being discussed, would appear to have been marginally sufficient at best (see again Figure 3). Nonetheless, the mortars had been used many times in the past to successfully fire single-break spherical shells and on occasion double-break spherical shells. If that was the case, why then did the mortar plug attachment fail on the occasion of being fired from the wooden barge deck? It can be surmised that on those past occasions, when the mortar plugs remained attached, the mortars had been placed on much more solid and unyielding support surface than the barge deck (such as illustrated in Figure 4). However, when the shells and mortars were fired on the relatively weak and flexible barge deck, the deck was unable to provide a sufficient upward force on the bottom of the mortar plug to approximately balance the downward force from the lift gas (such as illustrated Figure 5). This resulted in a substantially greater stress on the mortar plug attachment; more stress than it was capable of withstanding. Accordingly, what had proven sufficiently strong attachment in the past was not sufficient for the relatively weak and flexible barge deck.

As regards the failure of the barge deck, it can reasonably be concluded that there were two factors that combined to produce the deck failure, one fairly obvious and one not so obvious. The fairly obvious factor is that the internal mortar pressures for double-break spherical shells are expected to have been roughly double that for typical single-break spherical shells,[c] thus producing recoil forces also approximately double[g] and requiring a support surface with a correspondingly greater strength.

The not so obvious factor is associated with the design of the three mortar racks. For a ruggedly designed mortar rack, one with substantial support running the length of the rack below the mortars, the recoil force produced by the firing of individual mortars will be delivered somewhat uniformly across the entire area below the rack. In addition, when multiple racks are held tightly together as a single unit, to some extent the load will be further distributed across a wider area below the group of racks. In such a situation, the load strength (in pounds per square foot) of the support surface can be relatively modest. However, in the incident described above, the racks were made of fairly thin and narrow angle iron, with no interconnection between the two pieces of angle iron forming the bottom of the rack except at the two ends of the rack (see again Figure 3). In addition, the racks were loosely held together in such a way that allowed virtually free vertical movement of the individual racks. One can imagine that these racks will perform reasonably well when positioned vertically on a strong and unyielding support surface. However, such is not the case when the mortars in these racks are fired from a relatively weak and flexible surface.

When racks such as in this incident are fired from a relatively weak and flexible support surface, the recoiling mortars will cause the thin angle iron to twist and spread apart, even to the point of potentially allowing the mortars to slip between the two pieces of angle iron. When that happens, the recoil force from each individual firing mortar is applied to only that relatively small area of the barge deck immediately below the firing mortar. With the full mortar recoil force being applied to such a small area of the barge deck, for the deck to successfully withstand that concentrated force requires that the deck have substantially greater load strength. Then too, once the barge deck begins to fail at one point, the remaining load strength of the barge deck is lessened and the collective individual firings of the other mortars can more easily continue the process of deck failure, ultimately producing a total failure of the deck such as documented in Figure 2.

It is hoped that the discussion of the incident has provided some useful information that might be helpful to others in avoiding similar problems when firing a display from a relatively weak and flexible mortar support surface.[h]

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Notes

a) As is often the case when investigating accidents, some of the facts may be in dispute. For the purpose of this article, the details presented are as thought to be correct by the authors.

b) Double-break spherical aerial shells are also sometimes called peanut shells or double-bubble shells.

c) Estimates of the internal mortar pressures were generated using data produced by T. Shimizu's internal ballistics model[1] and with the assistance of J. Mercer using his ballistics model.[2]

d) Not shown in Figure 4 are the outward forces from the lift gas pressure acting in opposing directions on the mortar walls, which are thus balanced around the circumference of the mortar. It is primarily on the aerial shell where the force from the high pressure lift gas is not balanced, and this is what causes the shell to accelerate rapidly up the length of the mortar.

e) In the case of a strong and unyielding support surface, Newton's Second Law of Motion (F = m a) implies that for there to be no motion of the mortar plug upon firing (i.e., for the plug not be accelerated) there must be no net force on it (i.e., the force from the lift gas must be counter-balanced with an equal and opposite force provided by the support under the mortar).

f) This was confirmed by rough measurements suggesting that the upward force from the escaping gas around the shell acting to lift the mortar tube from the plug is only about 5 to 10% of the downward force acting on the mortar plug because of the pressure of the lift gas. In another test, a shell was fired from a mortar placed on a very strong and unyielding surface (a thick concrete slab). The mortar plug was not attached to the mortar in any way and was loose enough to slip out of the mortar tube when raised off the surface. When the shell fired, it was propelled to roughly half its normal height, the mortar plug did not noticeably move, and the mortar tube lifted off of the mortar plug and rose roughly two feet into the air.

g) Estimates of the recoil forces were derived from peak and average internal mortar pressures using the method described previously.[3]

h) Somewhat similar lack of support problems can occur even when firing from a strong and unyielding support surface, when that firing is from angled mortars. This is because the entire bottom of the mortar (or mortar rack) is not firmly resting against the supporting surface. The portion of the mortar plug that is not in contact with the support surface will not have the benefit of an upward force to balance the downward force from the lift gas pressure acting on the plug. In the incident being described in this article, note that two of the three mortars in each rack were angled slightly (fanned outward). This can be expected to have further increased the tendency for the mortars to slip through the bottom of the racks. In addition, the angling will further increase the tendency for the recoiling mortars to break through the barge deck, because the recoil force is concentrated along only that portion of the edge of the plug that first makes contact with the deck.

References

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2) "Thermodynamics of Black Powder and Aerodynamics of Propelled Aerial Shells", J. E. Mercer, *Journal of Pyrotechnics*, No. 16, 2002.
3) "Typical Mortar Recoil Forces for Spherical Aerial Shell Firings", K. L. Kosanke and L. Weinman, *Fireworks Business*, No. 242, 2004; *Selected Pyrotechnic Publications of K. L. and B. J. Kosanke, Part 7 (2003 and 2004),* 2006.