Fragmenting Steel Firework Mortar Tubes

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ABSTRACT

Firework maroon shells were exploded inside mild steel spiral wound mortar tubes with various mitigation systems in place. It was found that the number of fragments was substantially reduced when the tube was prevented from expanding freely by sandbags or by burial of the tube in sand. For mitigation systems that allowed free expansion of the tube, the number of fragments was similar to that produced when no mitigation was employed. Mitigation systems should extend to the top of the tube to prevent fragments from hitting spectators or operators at displays.

Keywords: firework, mortar tube, safety, fragment, mitigation, steel, sandbag

Introduction

When steel tubes are used to launch firework shells a major hazard occurs when the lifting charge of the shell fails to ignite and the bursting charge explodes when the shell is still in the mortar tube. This can cause the mortar tube to fragment resulting in the production of energetic projectiles. Such accidents have resulted in fatalities in Japan[1] and the United States[2] and severe injuries to operators and spectators.[1,3–5] An accident of this type occurred at the Glasgow Garden Festival in 1988, as a result of which a firework display operator had to have his leg amputated. Six spectators were also injured.[1] Following this, the UK Health and Safety Executive initiated research into mortar fragment hazards.

Previous work in the literature has shown that the premature explosion of maroon shells in 0.8 mm wall thickness mild steel tubes can cause fragments with masses of up to 200 g to be produced[6] and that they can be projected up to 120 metres.[7] In addition, other work[8] has shown that mortar fragments with masses of up to 100 g are capable of travelling at 512 m/s. Fragments of this type have sufficient energy to cause severe penetrative injuries while larger, slower moving fragments could also cause injuries by blunt trauma.[9] Clearly, it would be unacceptable if such fragments hit spectators at a display. Therefore, methods are needed to ensure that the fragments are prevented from reaching spectators or operators. Methods in current use include the implementation of large safety distances, remote firing, burying the mortar tubes in the ground, containing them within sand- or earth-filled barrels, or surrounding them with sandbags. A survey of current UK fireworks practice that covered mitigation methods[10] indicated a fairly extensive use of partially buried mortar tubes, especially for the larger calibres, but only rarely was the exposed portion of the mortar tube protected.

The aim of the present work is to compare the effectiveness of two ‘contact’ mitigation methods (sandbags and burial in sand-filled barrels), and a system using tyres, which allows free expansion of the mortar tube, as a means of mitigating the effects of fragments created by the explosion of shells in spiral wound steel mortar tubes. Tyres are a recognised form of screening to reduce projectile hazards in the demolition industry.[11,12]

Experimental

Mass and linear distance measurements made during this work can be traced to National Standards.

The shell and mortar tube combinations that had been shown to produce the largest number of fragments in previous work were used.[13] Most trials used 75 and 152 mm calibre spiral wound tubes with maroon shells fired in them. A few firings were carried out in 160 mm tubes with effect multibreak shells. In all cases the lifting charge was removed, the shell inverted, and suspended in the mortar tube at the desired height. The spiral wound tubes were made from a 0.07% carbon steel, according to British Standard 1449, with mild steel base plates welded to the tubes using a Metal Inert Gas (MIG) technique. Lengths and wall thicknesses of mortar tubes are given in Table 1.

Table 1. Mortars Used in Fragmentation Trials.

Calibre (mm)	Wall Thickness (mm)	Length of Mortar Tube (mm)
75	1.65	600
152	2.00	1000
160	2.00	1000

The mitigation systems used were as follows:

Tyres: Used car tyres, intended to fit 13 inch (330 mm) diameter rims, were stacked on top of each other and tied together. Mortar tubes of 75 or 152 mm calibre were placed, free standing, centrally inside the stack. Tests in which the 75 mm shell was suspended half way up the mortar tube had tyres extending to the top of the tube or to the top of the shell. For shells fired half way up 152 mm tubes, the tyres extended to the top of the tube.

Barrels: Details of the barrels used are given in Table 2. Mortars were positioned on the major axis and sand was then placed in the barrels in layers 30 cm deep and tamped after each layer was added. The process was repeated until the sand was 20 mm from the top of the barrel for the 75 mm mortar tubes and flush with the top of the barrel for the 152/160 mm tubes. Trials were also carried out with mortar tubes placed in empty 220–225 litre barrels and 70 litre bins (Table 2). Sufficient sand (<10 cm) was put in the base of the barrel to allow the mortar tubes to remain upright. The distance from the outside of the tube to the inside of the barrel wall was 230 mm for 225 litre barrels with 75 mm tubes, 190 mm for 225 litre barrels with 152/160 mm tubes, and 150 mm for 70 litre bins with 75 mm tubes.

Table 2. Barrels used in Mitigation Trials.

Description of Barrel	Material	Height (mm)	Diameter (mm)	Volume (litres)	Wall Thickness (mm)
Extrusion blow moulded drum with compression moulded L-shaped rings top and bottom	HDPE	928.00	572.00	220.00	2.3
Extrusion blow moulded drum with two lifting/rolling hoops. Open top	HDPE	900.00	560.00	225.00	8.0
Electrically welded side seam, two pressed out rolling hoops.	Mild steel	965.00	585.00	225.00	1.0
Extrusion blow moulded plastic bin. Open top	HDPE	635.00	370.00	70.00	5.1

Sandbags: Woven polypropylene bags (lay-flat dimensions of 770 mm length × 335 mm width) were filled with sand and packed around the mortar tube. The bags were either stacked to a height level with the top of the tube or to a height level with the top of the shell, which was suspended half way up the tube. The distance from the outside of the mortar tube to the outside edge of the sandbag mitigation system was 240 mm, which was comparable with trials using 225 litre barrels.

Some of the sandbag and barrel mitigation experiments were carried out twice, once using dry sand and once using damp sand. The damp sand had a moisture content in the range 8.5–12.2% (w/w), the comparable range for dry sand was 0.4–2.6% (w/w). Moisture contents were determined gravimetrically.

Tests were carried out in the middle of a 4 m square Blast Cell which had wood-lined walls to trap high velocity fragments. To determine the effectiveness of the mitigation systems, fragments were classified as either penetrating into the wood lining of the Blast Cell, lying on the floor of the Blast Cell or being trapped in the mitigation system.

Results

Results for the 75 mm mortar tubes with various methods of mitigating the fragments are shown in Table 3 [at the end of the article] and Figure 1. These indicate that:

1. The number of fragments was greatly reduced by mitigation systems in intimate contact with the mortars, such as sandbags or sand-filled barrels, while the reduction in number of fragments was much less in the case of systems which had an air gap between the mortar tube and the mitigation systems, such as tyres or empty barrels.
2. The effectiveness of the mitigation system in retaining fragments was increased when it covered the full length of the tube, rather than extending only to the top of the shell.
3. The most hazardous situation occurred when a shell was exploded at the top of the mortar tube because more fragments escaped from the mitigation system with sufficient energy to penetrate into the wood lining of the Blast Cell.

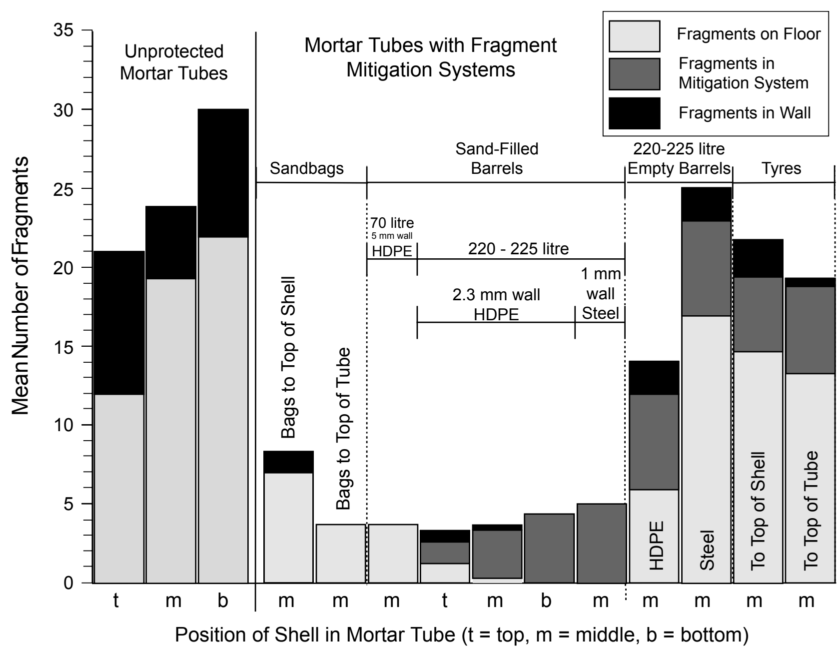

Figure 1. Distribution of fragments generated from 75 mm calibre spiral wound steel mortar tubes when maroon shells are exploded in them with various mitigation systems in place.

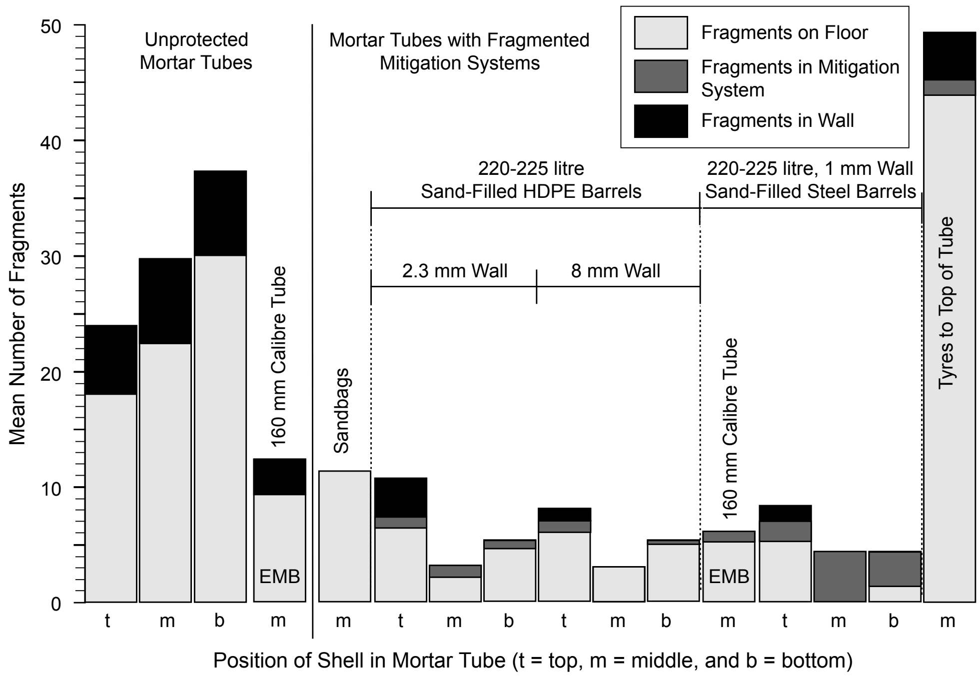

Figure 2. Distribution of fragments generated from 156/160 mm calibre spiral wound steel mortar tubes when maroon and effect multibreak shells (EMB) are exploded in them with various mitigation systems in place.

Similar results were found for maroon shells fired in 152 mm mortar tubes (Table 4 [at end of article] and Figure 2).

The effect of moisture content on the effectiveness of sand mitigation systems was unclear.[13] 75 mm tube trials showed an increase in the mean number of fragments generated when dry sand was used (4.7 fragments compared to 3.7 fragments for damp sand), while the 152 mm tube tests showed the reverse trend (11.3 fragments for damp sand compared to 6.7 fragments for dry sand). Since these data are inconclusive, and most sand used in the UK for this purpose would be damp, only the results from 'damp sand' trials have been included in this paper.

Tests with the 70 litre bin, using a maroon shell in a 75 mm mortar tube, showed that the mean number of fragments was reduced to 3.7, but that the plastic bin was totally destroyed. Inspection of the internal surfaces of the bin showed no witness marks. This indicated that the fragments from the mortar tube had not penetrated the 150 mm of sand between the tube and the bin wall, before the bin was destroyed by the pressure from the explosion.

Discussion

Previous work[13] has shown that when maroon shells are exploded in unmitigated 75 and 152 mm calibre mortar tubes, many small fragments of masses less than 50 g, and a few large fragments of masses greater than 400 g, are produced. Often the larger fragments originate from the baseplate or the main tube remote from the igniting shell. Similar tests using effect multibreak shells in 160 mm calibre spiral tubes produced substantially fewer fragments which were distributed approximately equally between these two mass groups.

Any fragment mitigation system must be able to cope with two distinct types of fragment:

1. fast-moving fragments (up to 512 m/s),[8] usually with masses less than 100 g,
2. slower fragments (up to 44 m/s),[8] often with masses greater than 400 g.

The former will present a hazard to both operators and spectators, while the latter are only likely to be hazardous to operators working within the safety zone between the fireworks and the spectators. To reduce hazards, a mitigation system can either catch the fragments formed by the pressure of the bursting charge, or it can both modify the fragmentation process and catch the fragments formed. Of the systems studied, empty barrels and tyres are systems that merely catch fragments, while sandbags, sand- or earth-filled barrels or, by implication, burial in the ground, are systems that modify the fragmentation behaviour, since they all reduce the number of fragments considerably (Figures 1 and 2).

If the fragmentation of an unmitigated tube is considered, the tube will expand in diameter as the internal pressure rises. When the tensile strength of the tube material is exceeded, which will occur at many points on the tube surface more or less simultaneously, the tube will fragment. For an unmitigated tube there will be little resistance to this expansion from the presence of the air outside the tube, whereas for a tube buried in sand there will be resistance to tube expansion from the mass of the sand in contact with the expanding tube. Thus there will be a smaller tensile strain in the tube, and fragmentation will start from fewer origins, creating a smaller number of fragments. Therefore, mitigation systems based on empty barrels or tyres will allow the tube to expand freely, and so the number of fragments produced with these mitigation systems will be similar to those produced in the absence of any mitigation system (Figures 1 and 2). If a tube is buried to anything less than its top, there is the possibility of the charge bursting in the unburied part of the mortar tube, which will produce a large number of fragments that will be free to fly unhindered by sand or soil. Repeat firings from mortar tubes that have been buried in the ground can cause a 'pile driving' effect, which causes the tube to be driven further into the ground with each firing.[14] In such cases, mitigation of the mortar by burying its full length in the ground would allow soil to fall into the tube as subsequent firings took place. The extent of 'pile-driving' could be reduced by increasing the area over which the recoil force acts (e.g., by placing wooden boards under the base of the mortar tube, or by using a wide collar at the tube neck which rests on the soil surface). This could be designed to be removable for transport purposes. Where 'pile-driving' is thought to be a problem, a hybrid mitigation system of partial burial and sandbagging of the portion of the mortar that protruded above the ground may be appropriate providing that the sandbags are placed in contact with the mortar tube to act as a barrier to tube expansion. The number of fragments is then likely to be reduced in a similar way to that achieved by full burial (Tables 3 and 4).

Mitigation systems should ideally be reusable. Since sandbags and 70 litre bins of sand were destroyed in the tests, this suggests that such mitigation systems will not be as suitable as either burying the full length of the mortar tube or using a large barrel. However, sandbags do have the advantage that they can be prepared before the day of the display and placed easily around the mortar tube. Also, Figures 1 and 2 indicate that although the sandbags were destroyed during the tests, no fragments were retrieved from the Blast Cell wall. This indicates that they have an effectiveness at reducing fragment travel comparable to that of sand filled barrels.

Conclusions

1. Steel mortar tubes should be surrounded by a mitigation system that covers the full length of the tube. One exception would be when spectators and operators firing the display are positioned beyond the foreseeable fragment travel range.
2. Mitigation systems such as sand-filled barrels and sandbags reduce the number of fragments as well as catching the fragments that are produced. These systems are therefore to be preferred to systems such as tyres or empty barrels, where there is no effect on the number of fragments generated.

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Table 3. Fragment Data from 75-mm Calibre Steel Mortar Tubes When Shells Have Been Exploded in Them While Using Different Mitigation Systems.

Position of Shell in Mitigation System	Type of Mitigation System Used	Mean Number of Fragments				Mean Mass of Fragments (g)	Mean Percentage Mass of Fragments		
		Total	In Wall	On Floor	In Mitigation		In Wall	On Floor	In Mitigation
75 mm maroon shell at top	Unmitigated	21.00	9.00	12.00	n/a	2471.00	6.60	93.40	n/a
	220–225 litre. 2.3 mm wall thickness HDPE barrel	3.30	0.70	1.00	1.30	2356.00	1.00	3.60	95.40
75 mm maroon shell at middle	Unmitigated	23.80	4.50	19.30	n/a	2458.00	5.80	94.20	n/a
	Empty 220–225 litre. 1.0 mm wall thickness steel barrel	25.00	2.00	17.00	6.00	2350.00	1.00	48.90	50.10
	Empty 220–225 litre. 2.3 mm wall thickness HDPE barrel	14.00	2.00	6.00	6.00	2352.00	1.30	6.80	91.90
	Tyres to top of shell	21.70	2.30	14.70	4.70	2290.00	1.50	70.40	28.10
	Tyres to top of tube	19.30	0.50	13.30	5.50	2277.00	0.60	51.40	48.00
	Sandbags to top of shell	8.30	1.30	7.00	n/a	2311.00	1.70	98.30	n/a
	Sandbags to top of tube	3.70	0.00	3.70	n/a	2359.00	0.00	100.00	n/a
	220–225 litre. 2.3 mm wall thickness HDPE barrel	3.70	0.30	0.30	3.00	2375.00	0.30	14.50	85.20
	220–225 litre. 1.0 mm wall thickness steel barrel	5.00	0.00	0.00	5.00	2270.00	0.00	0.00	100.00
	70 litre. 5.1 mm wall thickness HDPE bin	3.70	0.00	3.70	0.00	2379.00	0.00	100.00	0.00
75 mm maroon shell at bottom	Unmitigated	30.00	8.00	22.00	n/a	2450.00	8.20	91.80	n/a
	220–225 litre. 2.3 mm wall thickness HDPE barrel	4.30	0.00	0.00	4.30	2375.00	0.00	0.00	100.00

n/a = not applicable. For unmitigated firings no fragments can be retained in the mitigation system, while for sandbagging the mitigation system is destroyed leaving fragments on the floor or in the walls

Table 4: Fragment Data from 152/160 mm Calibre Steel Mortar Tubes When Shells Have Been Exploded in Them While Using Different Mitigation Systems.

Position of Shell in Mitigation System	Type of Mitigation System Used	Mean Number of Fragments				Mean Mass of Fragments (g)	Mean Percentage Mass of Fragments		
		Total	In Wall	On Floor	In Mitigation		In Wall	On Floor	In Mitigation
152 mm maroon shell at top	Unmitigated	24.00	6.00	18.00	n/a	9490.00	5.20	94.80	n/a
	220–225 litre 2.3 mm wall thickness HDPE barrel	10.70	3.30	6.30	1.00	10028.00	5.60	13.70	80.70
	220–225 litre 8.0 mm wall thickness HDPE barrel	8.00	1.00	6.00	1.00	10171.00	1.20	17.60	81.20
	220–225 litre 1.0 mm wall thickness steel barrel	8.30	1.30	5.30	1.70	10070.00	1.40	14.10	84.50
152 mm maroon shell at middle	Unmitigated	29.70	7.30	22.30	n/a	9357.00	3.30	96.70	n/a
	Tyres to top of tube	49.30	4.00	44.00	1.30	9927.00	0.70	51.70	47.60
	Sandbags to top of tube	11.30	0.00	11.30	n/a	9669.00	0.00	100.00	n/a
	220–225 litre 2.3 mm wall thickness HDPE barrel	3.70	0.00	2.70	1.00	9700.00	0.00	74.30	25.70
	220–225 litre 8.0 mm wall thickness HDPE barrel	3.00	0.00	3.00	0.00	9768.00	0.00	100.00	0.00
	220–225 litre 1.0 mm wall thickness steel barrel	4.30	0.00	0.00	4.30	9916.00	0.00	0.00	100.00
152 mm maroon shell at bottom	Unmitigated	37.30	7.30	30.00	n/a	9285.00	8.20	91.80	n/a
	220–225 litre 2.3 mm wall thickness HDPE barrel	5.30	0.00	4.70	0.70	9664.00	0.00	97.00	3.00
	220–225 litre 8.0 mm wall thickness HDPE barrel	5.30	0.00	5.00	0.30	9871.00	0.00	74.10	25.90
	220–225 litre 1.0 mm wall thickness steel barrel	4.70	0.00	1.70	3.00	9492.00	0.00	33.80	66.20
160 mm multibreak shell in middle	Unmitigated	12.30	3.00	9.30	n/a	10841.00	5.40	94.60	n/a
	220–225 litre 1.0 mm wall thickness steel barrel	6.00	0.00	5.00	1.00	10956.00	0.00	57.80	42.20

n/a = not applicable. For unmitigated firings no fragments can be retained in the mitigation system, while for sandbagging the mitigation system is destroyed leaving fragments on the floor or in the walls