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Estimating the TNT equivalence of a 15-ton single base powder explosion through damaged building profiles analyses

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Abstract

Back in 1964 President Vargas Works was the only place in the country which processed single base powder for the Brazilian Armed Forces. Then its industrial activity was quite strong and around 4:45 a.m. of 23rd September an intense decomposition of nearly 15 ton of that material took place in one of the production lines workshops. The consequences of this explosion were the destruction and extensive damage to the workshops around its epicenter. At that time pictures of all affected buildings were taken and their damages fully described. This led to the present work which consists in the evaluation of the TNT equivalent charge of the explosion using the concept of damage category developed by UK engineers based on the WWII damaging bombing data.

Keywords: TNT equivalent; Single base powder; Damage assessment; Explosion

1. Introduction

Accidents with large amounts of propellants or explosives may take place inside installations such as production lines or storage rooms or in the open, during loading operations or transportation.

The ability to evaluate possible damage in buildings and structures caused by these materials either under storage or while being transported is an essential requirement under any security procedures. Therefore, it is highly desirable to be able to foresee the degrees of damages caused by this type of accident.

Back in 1964 the only facility in the country to process single base powder for the Brazilian Armed Forces was the President Vargas Works (FPV), in Piquete, a town between the cities of Rio de Janeiro and São Paulo. Then its industrial activity was pursued around the clock and around 4:45 a.m. of 23rd September an intense decomposition of nearly 15 ton of that material took place in one of the production lines workshops.

The consequences of this explosion were the destruction and extensive damage to the workshops around its epicenter. At that time pictures of all affected buildings were taken and their damages fully described.

This led to the present work which consists in the evaluation of the TNT equivalent charge of the explosion using the concept of damage category developed by UK engineers based on the WWII damaging bombing data [1–3].

This method, described by Merrifield and Mackenzie [1], essentially divides the damaged buildings into five categories (here increased to 10, due to the extensive damage) and allows for the establishment of a relationship between damage and distance, i.e., of the destruction profile. This technique was chosen due to the fact that it was first developed envisaging brick houses as main targets which happened to be the main construction material of the above mentioned plant.

The mean TNT equivalent charge was calculated and compared with the TNT equivalent charge for each category, the maximum data departure being less than 10%, as expected.

Finally, this mean value, corrected to account for containing effects, yielded a 7% departure from the TNT equivalent value of the actual explosion, thus displaying the sound applicability of this technique.

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Table 1
Damage category and description (taken from Ref. [1])

Damage category	Damage description
A	Houses completely demolished, i.e., with over 75% of the external brickwork demolished
B	Houses so badly damaged that they are beyond repair and must be demolished when the opportunity arises. Property is included in this category if 50–75% of the external brickwork is destroyed, or in the case of less severe destruction, the remaining wall have gaping cracks rendering them unsafe
Cb	Houses which are rendered uninhabitable by serious damage, needing such an extensive repair that they must be postponed until after war. Example of damage resulting in such conditions include partial or total collapse of roof structures, partial demolition of one or two external walls up to 25% of whole, and severe damage of load-bearing partitions necessitating demolition and replacement
Ca	Houses that are rendered uninhabitable, but can be repaired reasonably quickly even under war time conditions, the damage sustained not exceeding minor structural damage, and partitions and joinery wrench from fixings
D	Houses requiring repairs to remedy serious inconveniences, but remaining habitable. Houses in this category may have sustained damage to ceilings and tilling, battens and roof covering, and minor fragment effects on wall and window glazing. Cases in which the only damage amounts to broken glass in less than 10% of the windows are not included

2. Model description

Following Merrifield and Mackenzie [1], buildings damaged by explosions can be categorized into four classes according to their damage assessment, as shown in Table 1.

They also suggested that the relation between W (kg), the explosive mass, and R_i (m), the distance from the explosion epicenter as related to the specific damage category, i, to be given by

$$R_i = \frac{k_i W^{1/3}}{\left[1 + (3175/W)^2\right]^{1/6}} \tag{1}$$

where $k_i = 4.8$, 7.1, 12.4, 21.3 and 42.6 for categories A, B, Cb, Ca and D, respectively.

As already mentioned, this technique was first developed to describe the damage caused to brick houses typical of the U.K. during WWII. This was quite convenient here in this work, for most of the facility buildings at the time of the accident were made of the same material.

Fig. 1. Single base powder boxes storage depot. Picture taken 50 m from epicenter.

3. Model upgrading

The damaged buildings detailed description available in Ref. [4] were contained within a radius of nearly 1500 m from the explosion epicenter, so that a pattern showing "the destruction profile" could be established. This allowed the damage to be assessed through some relevant structural aspects. In this work, it has been decided to choose the brickwork and the roof as the relevant aspects to be taken into consideration. This procedure led the brickwork and roof damages to be graded into three and six classes respectively, each one ordained from the more severe to the lightest damage. More than 200 pictures were studied and some of them are presented here in Figs. 1–12. This allowed the establishing of the following classification:

Brickwork:

(a) *Complete demolition*: At least one wall has crashed as shown in Figs. 1–4.
(b) *Partial demolition*: At least one wall shows severe cracks and crashing is imminent of follow as displayed in Fig. 5.

Fig. 2. Machine shop I. Picture taken 80 m from epicenter (obviously the bicycle belonged to the photographer).

Fig. 3. Electric power room. Picture taken 80 m from epicenter.

(c) *Gaping cracks*: At least one wall shows cracks not too severe to need demolition as shown in Figs. 8 and 9.

Roof:

(a) Total collapse (as shown in Figs. 5–7).
(b) Partial collapse (as shown in Fig. 9).
(c) *Tiles* (*ceramic*) *pulled out*: The roof structure remains but more than 70% of tiles are pulled out, as it can be seen in Fig. 10.
(d) *Tiles* (*ceramic*) *displaced*: Less than 50% of tiles were pulled out, as shown in Fig. 12.
(e) *Tiles* (*ceramic*) *with cracks*: Small pieces of tile were found inside the building, unfortunately there is no picture available.

Fig. 4. Carpentry. Picture taken 110 m from epicenter.

Fig. 5. Machine shop II. Picture taken 140 m from epicenter.

(f) *Tiles* (*asbestos*) *displaced*: Asbestos tiles were displaced even when no damage were noticed in tiles (ceramic). Fig. 11, taken 240 m from the explosion epicenter shows this effect on the mess room roof. However, it is worth mentioning that displaced asbestos tiles were found as far as 740 m away from the explosion epicenter.

The above considerations led to Table 2.

Therefore, as many buildings sustained extensive damage so that a large number of samples was available, it has been decided to split each damage category described above into two new ones: one including the worst kind of damage within the category under consideration and the other including the lighter kind of damage pertaining that category. Table 3 summarizes this suggestion.

Fig. 6. Machine shop III. Picture taken 170 m from epicenter.

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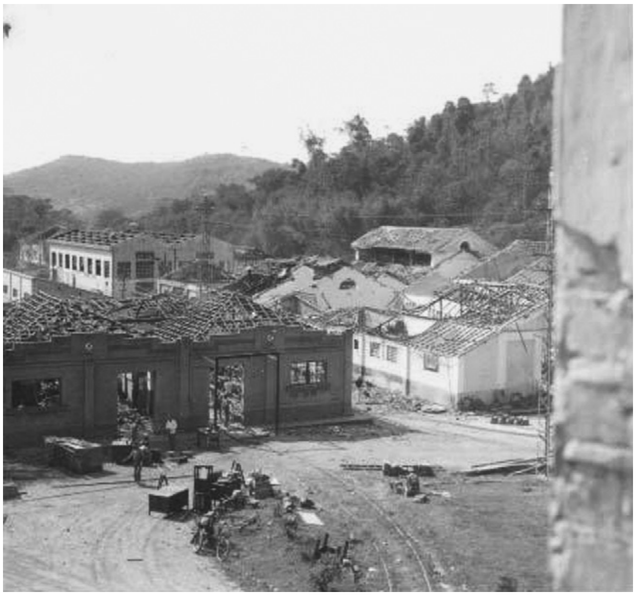

Fig. 7. General view of machine shops Yard. Picture taken 180 m from epicenter.

Fig. 8. Trucks repair shop. Picture taken 180 m from epicenter.

Table 3, along with pictures taken immediately after the occurrence and detailed damage description led to the assembling of Table 4. As already mentioned, some of the photographs used in this work are displayed in Annex (taken from Ref. [4]).

Notice that no damage category A was found in this assessment.

The limits between adjoining categories were established taking the mean between the low end of one category and the high end of the next, exception made to the last one (i.e., category D), where it was chosen its low value.

This way the category limits came out as 125 m, 215 m, 390 m and 740 m for Categories B, Cb, Ca and D, respectively.

A partial TNT equivalent charge, $\bar{W}_o$, is then calculated choosing the ratio R_i/K_i as given by Eq. (1) to be the mean value among the several existing categories. For N existing categories (here $N = 4$, namely, B, Cb, Ca and D) this yields:

$$\frac{k_i \bar{W}_o^{1/3}}{\left[1 + (3175/\bar{W}_o)^2\right]^{1/6}} = \frac{1}{N}\sum_{i=1}^{N}\frac{R_i}{k_i} \qquad (2)$$

Table 2
Suggested categories for damage description

Damage category	Brickwork demolished	Partial demolition	Gaping cracks	Complete roof collapse	Partial roof collapse	Tiles pulled out	Tiles (ceramic) displaced	Cracked tiles (ceramic)	Tiles (asbestos) displaced
A	X			X					
B	X			X					
Cb		X	X	X	X				
Ca						X	X		
D								X	X

Table 3
Expanded damage categories

Damage category	Brickwork demolished	Partial demolition	Gaping cracks	Total collapse of roof	Partial collapse of roof	Tiles pulled out	Tiles displaced	Tiles with cracks	Asbestos displaced
A (high)	X (100%)			X					
A (low)	X (75%)			X					
B (high)	X (50%)			X					
B (low)	X (25%)			X					
Cb (high)		X		X					
Cb (low)			X		X				
Ca (high)						X			
Ca (low)							X		
D (high)								X	
D (low)									X

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Table 4
Damage sustained: distance assessment

Distance from epicenter (m)	Brickwork demolished	Partial demolition	Gaping cracks	Total collapse of roof	Partial collapse of roof	Tiles pulled out	Tiles displaced	Tiles with cracks	Asbestos tiles displaced	Damage category	High	Low
50	X			X						B		X
80	X			X						B	X	
110	X			X						B		X
140		X		X						Cb	X	
170		X		X						Cb	X	
180			X		X					Cb		X
190			X		X					Cb		X
240						X				Ca	X	
270						X				Ca	X	
340							X			Ca		X
370							X			Ca		X
410								X		D	X	
740									X	D		X

Fig. 9. Sales department building. Picture taken 190 m from epicenter.

Fig. 10. Fire department building. Picture taken 240 m from epicenter.

Choosing R_i to be the distance from the explosion epicenter corresponding to each damage category as estimated in Table 3 and the parameters k_i of damage category i ($k_i = 7.1$, 12.4, 21.3 and 42.6 for categories B, Cb, Ca and D, respectively) as mentioned earlier, Eq. (2) yields this TNT equivalent, $\bar{W}_o = 6186.74$ kg.

Table 5 compares the above with the results for the TNT equivalent obtained for each damage category using Eq. (1) and displays their relative errors with respect to $\bar{W}_o$.

Table 5
Comparison between $\bar{W}_o$ and the TNT equivalent of each damage category

Damage category	R_i (m)	W_i (TNT equivalent)	$\frac{W_i - \bar{W}_o}{\bar{W}_o} \times 100$
B	125	6142.83	−0.71
Cb	215	5915.83	−4.37
Ca	390	6778.41	9.3
D	740	5942.80	−3.4

However, it is well known that one does not recover all energy potentially available from the explosive. For TNT, the total energy available from its detonation (calculated from thermodynamic work function) is 1159 cal/g. This energy is split between the air blast and other work performed by the explosion.

Assuming that most of bombing over UK during WWII was done with fragmentation bombs then, by following the same reasoning done by Cooper [5], who cleverly discussed the explosive energy budget using as an example a cylinder of TNT encased in steel with $M/C = 1$ (i.e., the mass of steel, M, equal to the mass of the explosive charge, C). He showed that, from that initial value of ∼1160 cal/g only 660 cal/g was available to form the air blast wave (the remaining ∼500 cal/g having been spent on the expansion and fragmentation of the steel case). Therefore, the TNT equivalent, $\bar{W}_o$, obtained from Eq. (2) should be corrected by a factor K, so that the effective TNT equivalent, $\bar{W}$, will then be given by

$$\bar{W} = K\,\bar{W}_o \tag{3}$$

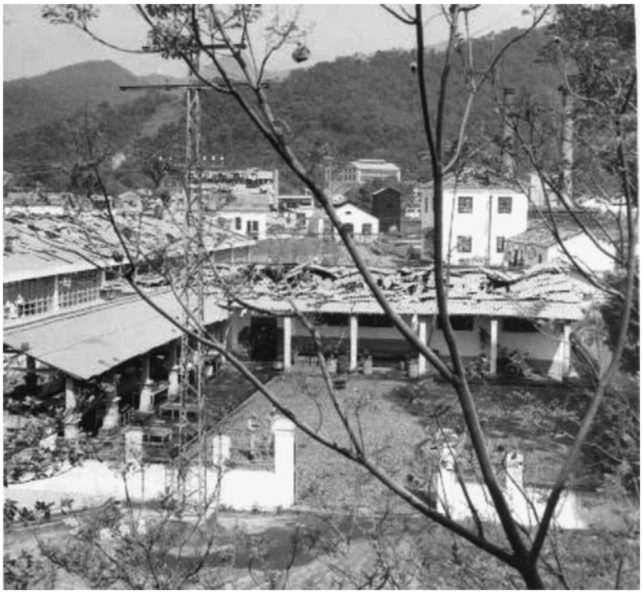

Fig. 11. Mess room. Picture taken 270 m from epicenter.

Fig. 12. Boiler room. Picture taken 340 m from epicenter.

From the above discussion K can be taken to be equal to $K = 1159/660 = 1.76$ This yields $\bar{W} = 1.76 \times 6186.74 = 10,888.66$ kg, i.e.,

$$\bar{W} = 10888.66\,\text{kg} \qquad (4)$$

for the TNT equivalent.

The single base powder total energy available was 921.0 cal/g (data taken from calorimetric measurements). For the total mass of 14740 kg which underwent explosion, one can calculate its TNT equivalent to be 17740.0 × (921.0/1159.0) = 11,713.15 kg. Eq. (4) compared with the above figure, yields a departure of 7%. Obviously this is due to unaccounted energy absorbing phenomena such as cratering. The crater mean diameter was 28.30 m according to Ref. [4]. However, it seems that the measurement was taken relative to the apparent crater diameter not to the actual one. Incidentally, a crater diameter of 23.86 m yields a TNT equivalent of 848.86 kg (using Yallop's equation as given in Ref. [6]) which happens to be the precise difference between the estimated value using the present technique (Eq. (4)) and the TNT equivalent of the actual exploding mass of Single Base Powder.

4. Conclusions

The use of the concept of damage category established by the UK engineers to assess the bombing effects during WWII led to the present work.

Fortunately the quality of the data collected at the time of the accident (and still available to the authors) were good enough. This allowed the damaged buildings categories to be doubled from 5 to 10, due to the observed extensive damage.

Therefore, the use of the above concept led to satisfactory results in the present case.

Finally it should be mentioned that most of this work has been presented at session 10C of the 30th DoD Explosives Safety Seminar, DDESB, Atlanta, Ga. 13–15 August, 2002.

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