Forensic Science International 252 (2015) 11–21

Contents lists available at ScienceDirect

Forensic Science International

journal homepage: www.elsevier.com/locate/forsciint

Forensic analysis of explosions: Inverse calculation of the charge mass

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ARTICLE INFO

Article history:
Received 30 January 2015
Received in revised form 8 April 2015
Accepted 10 April 2015
Available online 18 April 2015

Keywords:
Explosion
Forensic analysis
Blast
Debris
Damage
Statistical analysis

ABSTRACT

Forensic analysis of explosions consists of determining the point of origin, the explosive substance involved, and the charge mass. Within the EU FP7 project Hyperion, TNO developed the Inverse Explosion Analysis (TNO-IEA) tool to estimate the charge mass and point of origin based on observed damage around an explosion. In this paper, inverse models are presented based on two frequently occurring and reliable sources of information: window breakage and building damage. The models have been verified by applying them to the Enschede firework disaster and the Khobar tower attack. Furthermore, a statistical method has been developed to combine the various types of data, in order to determine an overall charge mass distribution.

In relatively open environments, like for the Enschede firework disaster, the models generate realistic charge masses that are consistent with values found in forensic literature. The spread predicted by the IEA tool is however larger than presented in the literature for these specific cases. This is also realistic due to the large inherent uncertainties in a forensic analysis. The IEA-models give a reasonable first order estimate of the charge mass in a densely built urban environment, such as for the Khobar tower attack. Due to blast shielding effects which are not taken into account in the IEA tool, this is usually an under prediction. To obtain more accurate predictions, the application of Computational Fluid Dynamics (CFD) simulations is advised.

The TNO IEA tool gives unique possibilities to inversely calculate the TNT equivalent charge mass based on a large variety of explosion effects and observations. The IEA tool enables forensic analysts, also those who are not experts on explosion effects, to perform an analysis with a largely reduced effort.

1. Introduction

Forensic analysis of explosions consists of determining the point of origin, the explosive substance involved, and the charge mass. In the case of deliberate explosions, this information is desirable to trace production facilities of illicit materials and eventually the perpetrator. In the case of accidental explosions, this information is important to identify the cause of the explosion, and to develop appropriate safety measures.

Although literature on post blast forensic investigation [1–3] contains a wealth of information, the descriptions are mainly qualitative. Furthermore, the focus is on collecting explosive residues and possible remains of a bomb. The current paper presents a quantitative method to estimate the TNT equivalent charge mass and point of origin based on observed damage around the explosion.

Two frequently occurring and reliable sources of information are observations on window breakage and building damage [11–14]. Also the size of a crater, fireball diameter, break-up of an enclosure in which the bomb is located, and debris throw of the enclosure may provide valuable information. For the various phenomena we have developed inverse models, which give an estimate of the charge mass (including an error) typically as a function of damage level and distance. These models have been implemented in the TNO Inverse Explosion Analysis (IEA) tool, which was developed for on-site application by a forensic analyst [21]. The tool enables the user to define evidence locations based on OpenStreetMaps, and add specific damage information. An example is given in Fig. 1 for the entry of window breakage evidence.

Terrorist bombing attacks and accidental explosions are often humanitarian disasters. Although the number of fatalities and injured people may exhibit a correlation with charge mass, we did not use this information for inverse calculations. The reason is the large inherent uncertainty in the location of people during the explosion, their protection and vulnerability.

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http://dx.doi.org/10.1016/j.forsciint.2015.04.014
0379-0738/

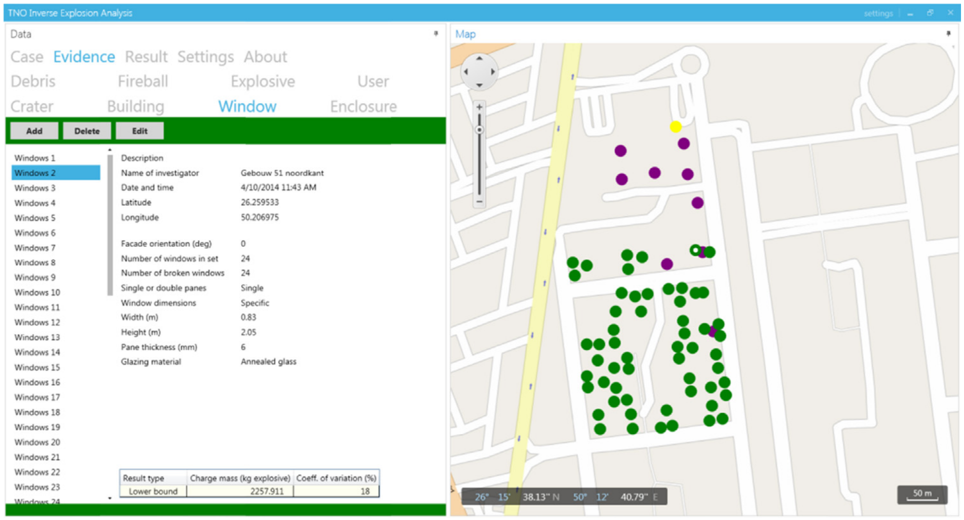

Fig. 1. Screenshot of the TNO IEA tool. Evidence tab with window breakage evidence entry [21].

The application of the method is limited to explosives which can be reasonably well represented by a TNT equivalency based on blast. These are typically high explosives with a large velocity of detonation and brisance such as TNT, RDX, and PETN. The concept of TNT equivalency has its limitations: different values can be found in the literature depending on whether it is based on overpressure or impulse, and the TNT equivalency can also depend on distance. For improvised explosives, including secondary combustion, and fireworks these deviations typically increase. The error made with the TNT equivalency should always be regarded together with other uncertainties, and as will become clear from the paper, these can be substantial. Gas and dust explosions should not be analysed with the IEA tool.

The inverse calculations lead to a set of charge mass estimates with varying reliability. Furthermore, some estimates give just a lower or upper bound. A statistical method has been developed to combine the various types of data, and to determine an overall charge mass distribution. This method is presented in Section 2.

In order to limit the scope of the paper, we focus in Sections 3 and 4 on the inverse models that have been developed for building damage and window breakage. These models are verified by their application to the Enschede firework disaster in 2000 [12–14] and the Khobar tower attack in 1996 [15–18] respectively. The blast shielding effect in a densely built urban area is not taken into account in the relatively simple inverse models. This effect is illustrated with Computational Fluid Dynamics (CFD) simulations of the blast propagation in the Khobar tower geometry, and modelling of the window response with a Single Degree of Freedom (SDOF) model. In Section 5 conclusions are presented.

2. Combining multiple charge mass predictions

The post blast evidence leads, together with an assumed point of origin, to multiple charge mass predictions including an error estimate. The charge mass predictions can be of three types. In the first type, the observed damage can be translated to a prediction of the blast strength, which can be translated to a single value prediction of the charge mass. However, many objects, e.g. windows, are either undamaged or completely broken. When such an object is broken, the result is a lower bound of the charge mass, while an undamaged object leads to an upper bound prediction. Practical considerations like the maximum load capacity of the vehicle used to carry the bomb may also lead to upper bounds. Single valued charge mass predictions are the most reliable type of data. Examples are façades where a part of the windows failed or where the building was damaged at an intermediate level.

In this section we present a method to determine an overall charge mass distribution based on the data types described above. The method is an extension of the least squares method.

2.1. The least squares method for single valued data

For a collection of N single valued charge mass predictions M_i, the sum of squared residuals R is:

$$R(M) = \sum_{i=1}^{N} (M_i - M)^2 \tag{1}$$

The average charge mass is defined as the M at which R has a minimum, i.e. where $dR/dM = 0$. This requirement leads directly to the arithmetic mean. When error estimates are available for each of the predictions, the charge masses can be characterized by their mean charge mass μ_i, and standard deviation $\sigma_i : M_i = (\mu_i, \sigma_i)$. In order to account for the error, the weighted sum of squared residuals can be defined as follows:

$$wR(M) = \sum_{i=1}^{N} \frac{1}{\sigma_i^2} (\mu_i - M)^2 \tag{2}$$

Minimization of this function shifts the average M towards data points with a smaller standard deviation. This is illustrated with an example in Fig. 2.

The resulting average charge mass and standard deviation of the average are given by:

$$M_{av} = \frac{\sum_{i=1}^{N} \frac{1}{\sigma_i^2} \cdot \mu_i}{\sum_{i=1}^{N} \frac{1}{\sigma_i^2}} \tag{3}$$

$$\sigma_M = \sqrt{\frac{\sum_{i=1}^{N} \frac{1}{\sigma_i^2} \cdot (\sigma_i^2 + {\mu_i}^2)}{\sum_{i=1}^{N} \frac{1}{\sigma_i^2}} - M_{av}^2} \tag{4}$$