Journal of Hazardous Materials 159 (2008) 264–270

Contents lists available at ScienceDirect

Journal of Hazardous Materials

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

Consequence analysis to determine damage to buildings from vapour cloud explosions using characteristic curves

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ARTICLE INFO

Article history:
Received 8 July 2007
Received in revised form 2 February 2008
Accepted 12 February 2008
Available online 16 February 2008

Keywords:
Vapour cloud explosion, VCE
Overpressure
Impulse
Damage to buildings
Consequence analysis
Characteristic curves

ABSTRACT

The objective of this paper is to propose a methodology to estimate the consequences to buildings from the pressure wave caused by unconfined vapour cloud explosions (VCEs). This methodology is based on the use of characteristic overpressure–impulse–distance curves, shown in a previous paper [F. Diaz Alonso, E. Gonzalez Ferradas, J.F. Sanchez Perez, A. Miñana Aznar, J. Ruiz Gimeno, J. Martinez Alonso, Characteristic overpressure–impulse–distance curves for vapour cloud, explosions using the TNO Multi-Energy model, J. Hazard. Mater. A137 (2006) 734–741]. They allow the overpressure and impulse at each distance from the explosion to be determined. Since they can be combined with damage criteria (such as those shown by the PROBIT equations), they can be used to perform consequence analysis as the damage is shown in the same diagram as the overpressure, impulse and distance. Since damages suffered by buildings usually affect people inside, it is important to take them into account when performing consequence analysis. This is done in this paper, where diagrams and equations are presented to determine minor damage to buildings (broken windows, displacement of doors and window frames, tile displacement, etc.), major structural damage (cracks in walls, collapse of some walls) and collapse (the damage is so extensive that the building is partially or totally demolished). This paper completes the consequence analysis to humans outdoors shown by F.D. Alonso et al. [F. Diaz Alonso, E. Gonzalez Ferradas, T. Jimenez Sanchez, A. Miñana Aznar, J. Ruiz Gimeno, J. Martinez Alonso, Consequence analysis to determine the damage to humans from vapour cloud explosions using characteristic curves, J. Hazard. Mater., in press].

1. Introduction

Characteristic overpressure–impulse–distance curves for vapour cloud explosions (VCEs) have been presented elsewhere [1]. They provide the most relevant information about explosions, namely the relationship between overpressure, impulse and distance. They are shown in Fig. 1, where the characteristic curves for VCEs with Multi-Energy charge strength of 10 are shown and the explosion occurred in Flixborough in June 1, 1974 is highlighted. In this accident a cyclohexane cloud of 30 tonnes exploded at the Nypro site in Flixborough, UK, releasing 1.4×10^{12} J of explosive energy and causing the death of 28 men and severe damage to buildings in the surroundings [1]. This explosion is used in this paper as an example of application of the proposed methodology.

VCEs are serious hazards in the refining and petrochemical industries [2]. Thus, a considerable amount of attention and research effort has been focused on this subject [3]. The use of models to determine the overpressure and impulse is justified, taking into account that they are the main parameters responsible for damage. In particular, their magnitudes are calculated in order to perform consequence analysis [4–9]. Before these characteristic curves were presented, to carry out consequence analysis it was necessary to run a model that could describe properly the behaviour of VCEs (usually the TNO Multi-Energy model [10]) once for each distance to obtain the overpressure and impulse. It was then necessary to determine what degree of damage would be expected at each of these distances. This can be done by taking into account certain damage criteria, which can be obtained from tables that relate various overpressure–impulse combinations to the expected degree of damage [11], as well as from the PROBIT equations [12]. These equations relate the magnitude of the danger to the percentage of the exposed buildings that will suffer a certain degree of damage. They are used here, since they are one of the most extended methodologies for determining the damage caused by industrial accidents [13]. By combining the characteristic curves with the PROBIT equations, damage can be easily and directly assessed in only one step, which simplifies the methodology and allows for a greater number of determinations in a

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doi:10.1016/j.jhazmat.2008.02.015

Nomenclature

a and c	fitting parameters used by Diaz Alonso et al. (2006) to build the *characteristic curves* (Pa and Pa s, respectively)
A and B	constant parameters in PROBIT equations (dimensionless)
b and d	fitting parameters used by Diaz Alonso et al. (2006) to build the *characteristic curves* (dimensionless)
E_{exp}	explosion energy (J)
F	factor included in the ln of PROBIT equations. It reflects the contribution of dangerous magnitudes to damage (different dimensions depending on the type of damage)
F'	factor used to develop fundamental equations. It is a modified F factor, since it does not depend on dangerous magnitudes (P_s or i), but on distance and explosion energy (different dimensions depending on the type of damage)
i	impulse (Pa s)
N	multi-energy charge strength (dimensionless)
P_s	side-on overpressure (Pa)
R	percentage of building damage (%)
S and T	constant parameters used to obtain a modified PROBIT expression (dimensionless)
Y	PROBIT (dimensionless)
z	distance to the explosion's center (m)

shorter time. In this paper, the necessary information is provided to determine minor damage to buildings (broken windows, displacement of doors and window frames, tile displacement, etc.), major structural damage (cracks in walls, collapse of some walls) and collapse (the damage is so extensive that the building is partially or totally demolished). This methodology applies to vapour cloud explosions occurring outdoors and affecting buildings in the surroundings.

2. Description of PROBIT equations

Firstly, the PROBIT equations found in the literature for minor damage, major structural damage and building collapse are discussed and their suitability is compared with real data. PROBIT equations (Y) are in the general form shown by Eq. (1).

$$Y = A + B \ln F = A + B \ln[f(P_s, i)] \tag{1}$$

where A and B are constants depending on the type of damage and F is a function of the dangerous magnitudes (in the case of explosions F is a combination of overpressure, P_s and impulse, i).

The PROBIT (Y) can be related to the percentage of affected buildings (R, %) by means of a table published by [13], which is valid for every PROBIT equation. R–Y data from [13] have been fitted by means of Eq. (2), valid for R values between 5% and 95% of affected buildings.

$$R = -3.25 \cdot Y^3 + 48.76 \cdot Y^2 - 206.60 \cdot Y + 270.35 \tag{2}$$

PROBIT equations shown in Table 1 are those found in the literature for different types of damage to buildings from explosions.

To evaluate the suitability of these PROBIT equations, Eqs. (3)–(5), they are compared to real data from accidental explosions shown in Ref. [11]. This comparison is performed in Table 2, where it is shown that real data expressed in the columns "Damage description" and "Percentage of damage" are in good agreement with the results obtained from Eqs. (3)–(5). In particular, the percentages of damage shown in [11] fit with the percentage of building collapse. Furthermore, as shown by the column "References" from Table 1, these PROBIT equations are widely referenced in the most relevant literature in the field. For these reasons, these equations are considered suitable and are used in this paper to develop the methodology to determine damage to buildings from unconfined vapour cloud explosions.

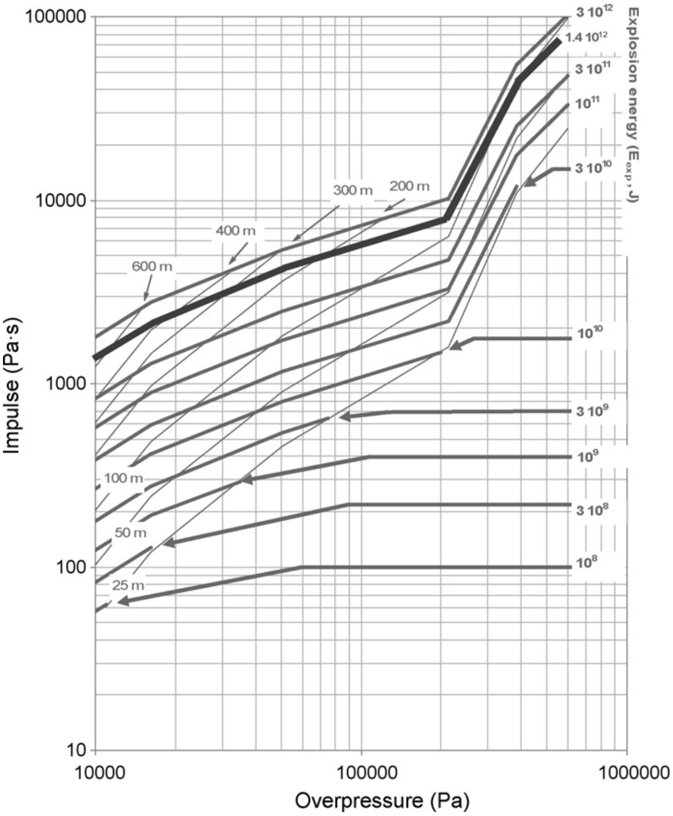

Fig. 1. Characteristic overpressure–impulse–distance curves for VCE with a Multi-Energy charge strength of 10. The Flixborough VCE (United Kingdom, 1974) is highlighted in bold.

The column "Corrected results" in Table 2 shows that results from Eqs. (3)–(5) must be corrected. Since they refer to different degrees of the same type of damage, lower levels of damage are also included in higher ones, that is, when a building suffers collapse, it is assumed that it is also affected by major structural damage and minor damage. For example, for overpressure of 18,600 Pa and impulse of 2300 Pa s, from Eqs. (3)–(5), the following results are obtained:

Minor damage, Eq. (3):

$Y = 6.41$ Percentage of affected buildings, from Eq. (2) = 92%

Major structural damage, Eq. (4):

$Y = 4.85$ Percentage of affected buildings, from Eq. (2)– = 55%

Collapse, Eq. (5):

$Y = 3.77$ Percentage of affected buildings, from Eq. (2) = 11%

These results must be corrected by the following steps:

Table 1
PROBIT equations for different degrees of damage to buildings caused by explosions

Type of damage	PROBIT equations	References
Minor damage (broken windows, displacement of doors and window frames, tile displacement, etc.)	$Y = 5 - 0.26\ln\left[\left(\frac{4600}{P_s}\right)^{3.9} + \left(\frac{110}{i}\right)^{5}\right]$ (3)	[11,13–15]
Major structural damage (cracks in walls, collapse of some walls)	$Y = 5 - 0.26\ln\left[\left(\frac{17500}{P_s}\right)^{8.4} + \left(\frac{290}{i}\right)^{9.3}\right]$ (4)	
Collapse (building partially or totally demolished)	$Y = 5 - 0.22\ln\left[\left(\frac{40000}{P_s}\right)^{7.4} + \left(\frac{460}{i}\right)^{11.3}\right]$ (5)	

Table 2
Comparison of Eqs. (3)–(5) with real data from accidental explosions shown by [11]

Information obtained from [11]				Results obtained from the application of Eqs. (3)–(5)	Corrected results
Overpressure (Pa)	Impulse (Pa s)	Damage description	Percentage of damage		
34,500	12,100	Serious damage. Requires demolition	40%	40% collapse >95% major damage >95% minor damage	40% collapse 55–60% major damage 0–5% minor damage 0% undamaged buildings
27,600	11,200	Moderated damage	25%	27% collapse 84% major damage >95% minor damage	27% collapse 57% major damage 11–16% minor damage 0–5% undamaged buildings
18,600	2,300	Minor damage (repairable)	10%	11% collapse 55% major damage 92% minor damage	11% collapse 44% major damage 37% minor damage 8% undamaged buildings

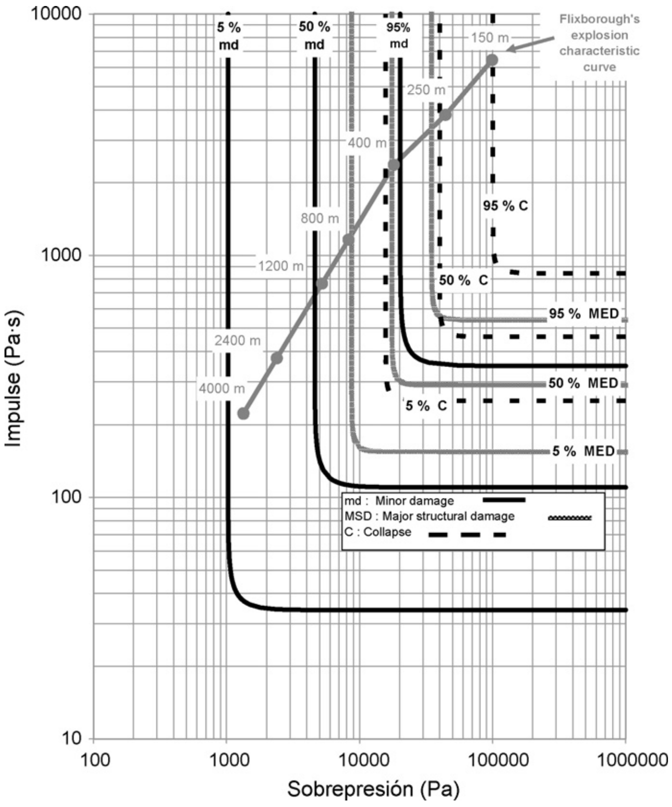

Fig. 2. Consequence analysis for buildings from the Flixborough vapour cloud explosion (releasing 1.4 × 10^{12} J and with a Multi-Energy charge strength of 10).

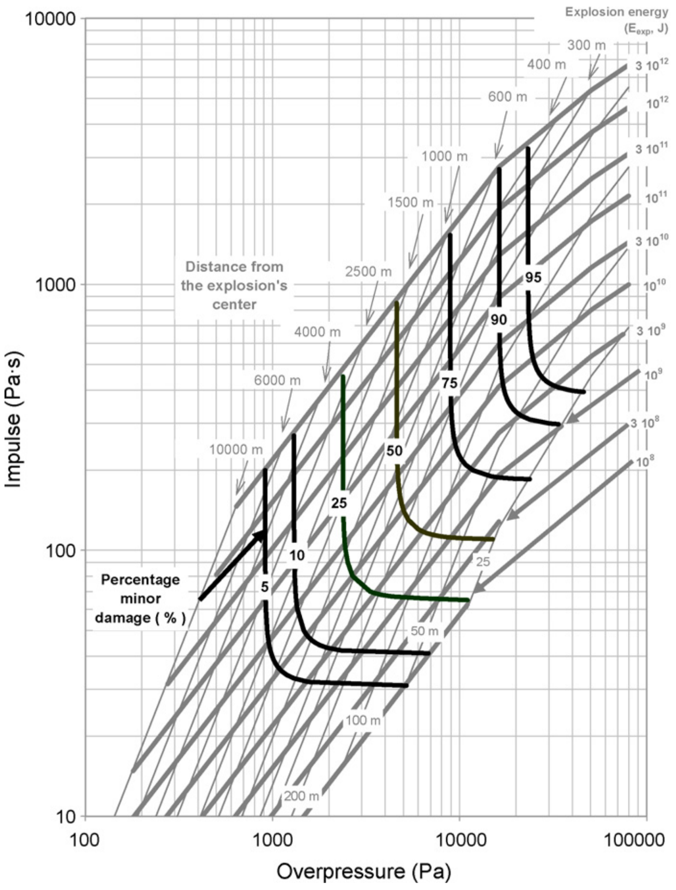

Fig. 3. Percentage of minor damage to buildings (black solid lines) as a function of distance (thin grey lines) and explosion energy (thick grey lines) for vapour cloud explosions with charge strength of 10, calculated using the TNO Multi-Energy model.

Table 3
Iso-damage curves for several levels of damage to buildings

Percentage of damage *R* (%)	PROBIT Y	Minor damage, Eq. (3)	Major structural damage, Eq. (4)	Building collapse, Eq. (5)
5	3.48	$i=110\left[\dfrac{1}{3.46\times10^{2}-(4600/P_s)^{3.9}}\right]^{1/5}$ (6)	$i=290\left[\dfrac{1}{3.46\times10^{2}-(17500/P_s)^{8.4}}\right]^{1/9.3}$ (7)	$i=460\left[\dfrac{1}{10^{3}-(40000/P_s)^{7.4}}\right]^{1/11.3}$ (8)
50	5.00	$i=110\left[\dfrac{1}{1-(4600/P_s)^{3.9}}\right]^{1/5}$ (9)	$i=290\left[\dfrac{1}{1-(17500/P_s)^{8.4}}\right]^{1/9.3}$ (10)	$i=460\left[\dfrac{1}{1-(40000/P_s)^{7.4}}\right]^{1/11.3}$ (11)
95	6.5	$i=110\left[\dfrac{1}{3.12\times10^{-3}-(4600/P_s)^{3.9}}\right]^{1/5}$ (12)	$i=290\left[\dfrac{1}{3.12\times10^{-3}-(17500/P_s)^{8.4}}\right]^{1/9.3}$ (13)	$i=460\left[\dfrac{1}{1.09\times10^{-3}-(40000/P_s)^{7.4}}\right]^{1/11.3}$ (14)

Table 4
Consequence analysis to buildings from the Flixborough's VCE

Distance from the explosion's centre (m)	Main damages on buildings (corrected values)
150	>95% collapse <5% rest
250	56% collapse 40% major structural damage <5% rest
400	14% collapse 50% major structural damage 28% minor damage 7% undamaged buildings
800	<5% collapse <5% major structural damage 67–72% minor damage 23–28% undamaged buildings
1200	<5% collapse <5% major structural damage 49–54% minor damage 46–51% undamaged buildings
2400	<5% collapse <5% major structural damage 20–25% minor damage 75–80% undamaged buildings
4000	<5% collapse <5% major structural damage 5–10% minor damage 90–95% undamaged buildings

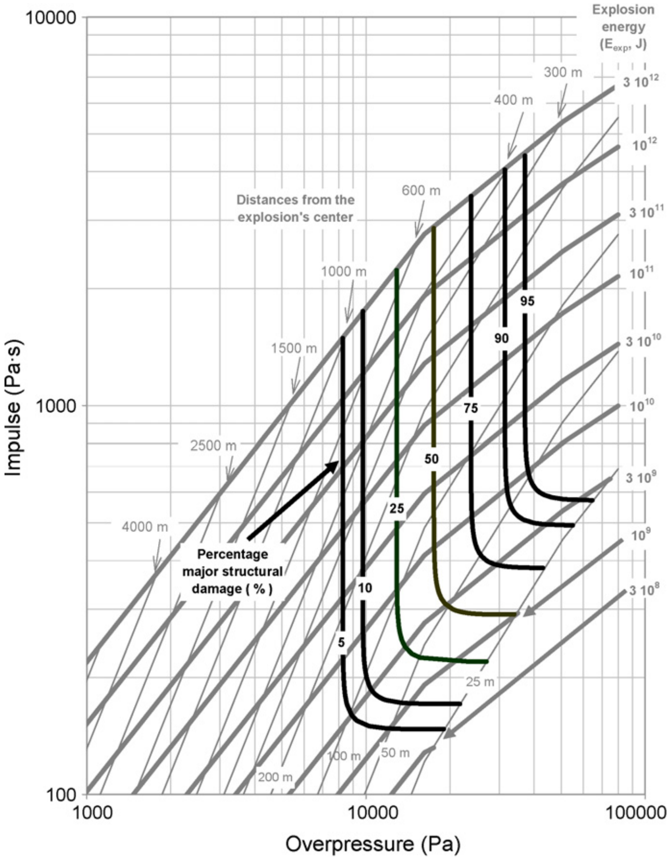

Fig. 4. Percentage of major damage to buildings (black solid lines) as a function of distance (thin grey lines) and explosion energy (thick grey lines) for vapour cloud explosions with charge strength of 10, calculated using the TNO Multi-Energy model.

1. The highest level of damage – collapse – must be used without modification (in this case, 11% of buildings are affected by collapse).
2. The actual percentage of buildings affected by major structural damage is obtained by subtracting the percentage of buildings suffering collapse from the percentage obtained from Eq. (4).

   Actual major structural damage : $55 - 11 = 44\%$

3. The actual percentage of minor damage is obtained by subtracting the other two percentages from the result obtained by means of Eq. (5):

   Actual minor damage : $92 - (44 + 11) = 37\%$

The remainder of the buildings $(100 - (37 + 44 + 11) = 8\%)$ are undamaged.

It must be stated that percentage of damage cannot be accurately established when it is higher than 95% or lower than 5%. In this cases the result is out of the validity interval of Eq. (2) and it must be expressed as >95% or <5%, respectively. Obviously, this leads to incertitude of 5% in the calculation of the respective corrected values.

3. Methodology

When the PROBIT equations have been selected, iso-damage curves are represented in the same diagram as the *characteristic curves* for vapour cloud explosions. This allows a direct relationship between expected degrees of damage and distance to the explosion's origin to be established. This methodology can be applied to every vapour cloud explosion whose explosion energy and Multi Energy charge strength are known, taking only these parameters and distance as inputs. To perform this operation the following steps must be carried out:

1.- Selected PROBIT equations are taken, in this case Eqs. (3)–(5).
2.- Target percentages of affected buildings are established (*R*). As an example 5, 50 and 95% are used in this paper. For these percentages *Y* values of 3.48, 5.00 and 6.5 are calculated, respectively, by means of Eq. (2).
3.- When these *Y* values are substituted in the PROBIT equations (3)–(5), the iso-damage curves are obtained, as shown in Table 3. For each level of damage and for each *R*-value, the iso-damage curves are characterized by the overpressure–impulse relationships shown by Eqs. (6)–(14).
4.- The curves obtained for the percentages selected in the previous step are represented in an overpressure–impulse diagram where the *characteristic curve* of the targeted explosion is overlaid. As an example, the above mentioned Flixborough explosion (characterized by Multi-Energy charge strength of 10 and explosion energy of 1.4×10^{12} J) has been represented in Fig. 2. The consequence analysis (main damages calculated as a function of distance) for this explosion is shown in Table 4.From the results of the consequence analysis, a main conclusion can be extracted. Damages to buildings (especially minor damage) occur even at greater distance from the explosion's center than those to people outdoors [16]. Thus, it is important to take into account damage to buildings when consequence analysis must be performed for accidental explosions.
5.- This methodology can be applied to a wide range of explosions. To carry out this operation, a set of *characteristic curves* (characterized by the explosion energy and Multi-Energy charge strength) can be represented together with the iso-damage curves (PROBIT equations corresponding to the selected percentages of affected population). As an example, in Figs. 3, 4 and 5 the *characteristic curves* for vapour cloud explosions with Multi-Energy charge strength of 10 together with the main iso-damage curves have been represented. For the rest of charge strengths (*N* = 1–9) similar diagrams can be built up from the data provided in Ref. [1].

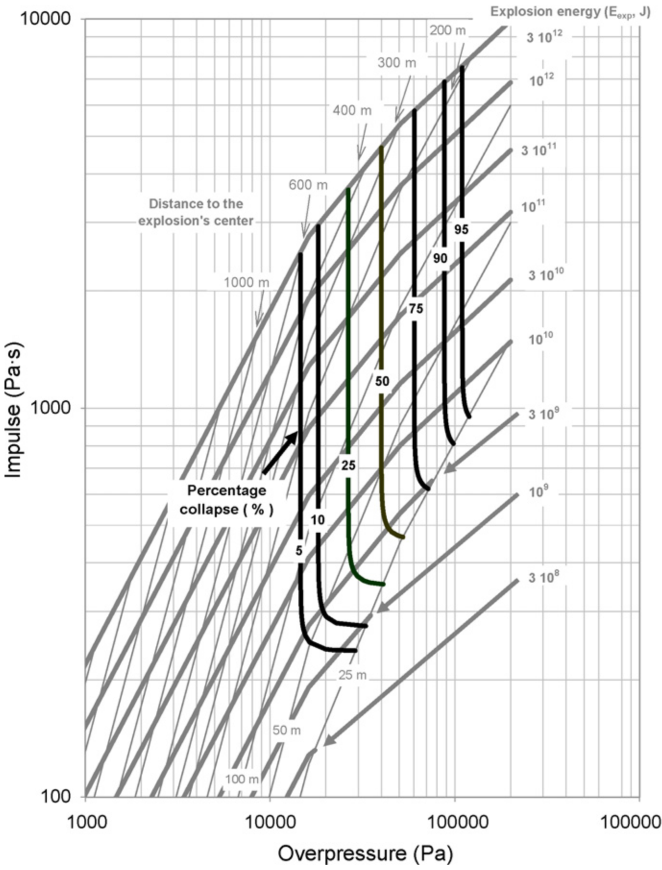

Fig. 5. Percentage of building collapse (black solid lines) as a function of distance (thin grey lines) and explosion energy (thick grey lines) for vapour cloud explosions with charge strength of 10, calculated using the TNO Multi-Energy model.

4. Numerical treatment

The diagrams of Figs. 3–5 are represented in a log–log scale, which can make difficult to perform an accurate reading. Furthermore, if this methodology is to be implemented in a computer model or a spreadsheet to allow a numerical estimation of the expected damage as a function of distance to the explosion's center, it is necessary to express analytically the iso-damage lines and the *characteristic curves*. These characteristic curves [1] can be expressed as a relationship between overpressure or impulse and explosion energy and distance, as shown by Eqs. (15) and (16).

$$P_s = a \cdot [f(z, E_{\text{exp}})]^b \tag{15}$$

$$i = c \cdot [f(z, E_{\text{exp}})]^d \tag{16}$$

where *a*, *b*, *c* and *d* are the fitting parameters used by [1].

Table 5
Modified PROBIT functions ($Y = S + T \ln F'$) to calculate the percentage of buildings that would suffer each type of damage caused by vapour cloud explosions

Type of damage	N	F'	Validity (interval of F')	$Y = S + T \ln F'$
Minor damage	2	$z/E_{\mathrm{exp}}^{1/3}$	From 1.18×10^{-3} to 3.14×10^{-2}	$-0.10 - \ln F'$
	3	$z/E_{\mathrm{exp}}^{1/3}$	From 2.79×10^{-3} to 7.43×10^{-2}	$0.76 - \ln F'$
	4	$\left[\left(\frac{32.75z}{E_{\mathrm{exp}}^{1/3}}\right)^{3.86} + \left(\frac{2.87\times 10^{4}z}{E_{\mathrm{exp}}^{2/3}}\right)^{4.85}\right]$	From 1.82×10^{-3} to 5.49×10^{2}	$5 - 0.26 \ln F'$
	5	$\left[\left(\frac{17.92z}{E_{exp}^{1/3}}\right)^{3.86} + \left(\frac{1.90\times 10^{4}z}{E_{\mathrm{exp}}^{2/3}}\right)^{5}\right]$	From 1.82×10^{-3} to 5.49×10^{2}	$5 - 0.26 \ln F'$
	6	$\left[\left(\frac{8.48z}{E_{\mathrm{exp}}^{1/3}}\right)^{4.33} + \left(\frac{1.19\times 10^{4}z}{E_{\mathrm{exp}}^{2/3}}\right)^{5.15}\right]$	From 1.82×10^{-3} to 5.49×10^{2}	$5 - 0.26 \ln F'$
	7	$\left[\left(\frac{7.51z}{E_{\mathrm{exp}}^{1/3}}\right)^{4.68} + \left(\frac{1.19\times 10^{4}z}{E_{\mathrm{exp}}^{2/3}}\right)^{5.15}\right]$	From 1.82×10^{-3} to 5.49×10^{2}	$5 - 0.26 \ln F'$
	8–10	$\left[\left(\frac{8.33z}{E_{\mathrm{exp}}^{1/3}}\right)^{4.41} + \left(\frac{1.19\times 10^{4}z}{E_{\mathrm{exp}}^{2/3}}\right)^{5.15}\right]$	From 1.82×10^{-3} to 5.49×10^{2}	$5 - 0.26 \ln F'$
Major structural damage	4	$z/E_{\mathrm{exp}}^{1/3}$	From 3.71×10^{-3} to 1.69×10^{-2}	$-5.45 - 2.16 \ln F'$
	5	$z/E_{\mathrm{exp}}^{1/3}$	From 6.74×10^{-3} to 3.08×10^{-2}	$-4.16 - 2.16 \ln F'$
	6	$\left[\left(\frac{28.27z}{E_{\mathrm{exp}}^{1/3}}\right)^{9.32} + \left(\frac{3.05\times 10^{4}z}{E_{\mathrm{exp}}^{2/3}}\right)^{9.58}\right]$	From 1.82×10^{-3} to 5.49×10^{2}	$5 - 0.26 \ln F'$
	7	$\left[\left(\frac{22.87z}{E_{\mathrm{exp}}^{1/3}}\right)^{10.08} + \left(\frac{3.05\times 10^{4}z}{E_{\mathrm{exp}}^{2/3}}\right)^{9.58}\right]$	From 1.82×10^{-3} to 5.49×10^{2}	$5 - 0.26 \ln F'$
	8–10	$\left[\left(\frac{24.84z}{E_{\mathrm{exp}}^{1/3}}\right)^{13.27} + \left(\frac{3.05\times 10^{4}z}{E_{\mathrm{exp}}^{2/3}}\right)^{9.58}\right]$	From 1.82×10^{-3} to 5.49×10^{2}	$5 - 0.26 \ln F'$; for $(z/E_{\mathrm{exp}}^{1/3}) \leq 4.3 \times 10^{-2}$
		$\left[\left(\frac{27.17z}{E_{\mathrm{exp}}^{1/3}}\right)^{9.49} + \left(\frac{3.05\times 10^{4}z}{E_{\mathrm{exp}}^{2/3}}\right)^{9.58}\right]$	From 1.82×10^{-3} to 5.49×10^{2}	$5 - 0.26 \ln F'$; for $(z/E_{\mathrm{exp}}^{1/3}) > 4.3 \times 10^{-2}$
Building collapse	5	$z/E_{\mathrm{exp}}^{1/3}$	From 2.24×10^{-3} to 1.72×10^{-2}	$-3.18 - 1.61 \ln F$
	6	$\left[\left(\frac{59.53z}{E_{\mathrm{exp}}^{1/3}}\right)^{8.21} + \left(\frac{4.78\times 10^{4}z}{E_{\mathrm{exp}}^{2/3}}\right)^{11.64}\right]$	From 5.79×10^{-4} to 1.73×10^{3}	$5 - 0.22 \ln F$
	7	$\left[\left(\frac{45.55z}{E_{\mathrm{exp}}^{1/3}}\right)^{8.88} + \left(\frac{4.78\times 10^{4}z}{E_{\mathrm{exp}}^{2/3}}\right)^{11.64}\right]$	From 5.79×10^{-4} to 1.73×10^{3}	$5 - 0.22 \ln F$
	8–10	$\left[\left(\frac{41.92z}{E_{\mathrm{exp}}^{1/3}}\right)^{11.69} + \left(\frac{4.78\times 10^{4}z}{E_{\mathrm{exp}}^{2/3}}\right)^{11.64}\right]$	From 5.79×10^{-4} to 1.73×10^{3}	$5 - 0.22 \ln F$

Combining Eqs. (15) and (16) with Eq. (1), equations relating PROBIT with explosion energy and distance to the explosion's center are obtained, as shown by Eq. (17).

$$Y = S + T\ \ln[f(z, E_{\mathrm{exp}})] = S + T\ \ln F' \tag{17}$$

where S and T are fitting parameters. Finally, the combination of Eqs. (2) and (17) allows establishing relationships between percentage of affected buildings for each explosion (characterized by its explosions energy and Multi-Energy charge strength) and distance to the explosion's center. In Table 5 the expressions of F' and Y are indicated, as well as the validity intervals for F' that must be taken into account to calculate Y.

Finally, the sequence to determine the level of building damage caused by the vapour cloud explosions using the numerical equations indicated in Table 5 is the following:

1. Determination of explosion energy (E_{exp}) and charge strength (N). These parameters define the explosion itself and can be calculated by means of the Multi-Energy model [10].

Table 6
Comparison between the real damage observed in the explosion occurred in Flixborough [17] with the results obtained from the application of the proposed methodology

Distance from the explosion's center, z (m)	Location [17]	Description of the damages observed in the accident scenario [17]	Results obtained using the proposed methodology
100	Nypro site	All the buildings and structures collapsed	>95% building collapse
400	House in Flixborough Stather	Roof collapsed and 75% of windows broken	15% collapse, 78% major + minor damage, 7% undamaged buildings
540	Group of 6 houses	Damages in roofs and external walls	<5% collapse, 20–25% major damage, 60% minor damage, 15% undamaged buildings
890	Flixborough Parkings Farm	Some cracks in walls and almost all the windows broken	<5% major damage, 60–65% minor damage, 30–35% undamaged buildings
1340	Neap House and Rose Cottage	Approximately 75% of broken windows	50% minor damage, 50% undamaged buildings
2750	Burton upon Stather	20% of broken windows	21% minor damage, 79% undamaged buildings

2. Selection of a distance at which the degree of damage will be determined.
3. Calculation of F' for each type of damage by means of Table 5.
4. Verification of interval for F' indicated in Table 5.
5. Calculation of Y by means of Table 5. It must be noted that PROBIT (Y) is not expressed as a function of overpressure and impulse, but of distance and explosion energy.
6. Calculation of R (percentage of affected buildings for each type of damage) by means of Eq. (2) and correction following the steps indicated in Section 2.

Finally, in order to test the reliability of the methodology here exposed, it is applied to the Flixborough explosion indicated above. A comparison is performed in Table 6 between the results obtained using the proposed methodology and the real damages observed in the accident [17]. As it can be observed, the methodology provides results that are in good agreement with the real damages observed in the accident.

5. Conclusions

The characteristic overpressure–impulse–distance curves [1] can be used to determine the overpressure and impulse in an industrial explosion caused by the ignition of a vapour cloud. But one of the most important applications of these curves is to use them to carry out consequence analysis. To perform this operation, PROBIT equations showing the relationship between the magnitudes of the danger (overpressure and impulse) and the percentage of affected buildings have been selected here and plotted on the same graph as the characteristic curves. As a result of this operation, damage to buildings can be directly assessed without the need for calculations and an overview of the evolution of damage caused by VCEs can be obtained. These figures also allow a comparison of the damage as a function of explosion energy and distance for the same or different charge strengths. When a more accurate result is needed, or when the methodology must be implemented by means of a computer program or a spreadsheet, the equations in Table 5 can be used. These allow the percentage of buildings affected by each type of damage to be obtained directly as a function of distance and explosion energy for each charge strength. In summary, this new methodology allows consequence analysis to be performed in a simpler and faster way.

Acknowledgements

This work is supported by the Spanish National Institute for Occupational Safety and Hygiene (INSHT) and the Spanish General Directorate for Civil Protection and Emergencies (DGPCE).

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