

ESTIMATION OF EXPLOSION DAMAGE TO URBAN STRUCTURES IN THE NETHERLANDS

by

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Abstract

As part of the work that is performed in a study concerning the risks that are involved in storage of explosive goods, estimations have been made of the damage that might occur to urban structures in case of an accident. These estimations determine the probability that a certain damage to a structure, or structural element, will occur as a function of some blastwave parameters. The structures involved in this study are primarily urban structures consisting of load bearing walls with various structural elements such as brickwork partition walls, prefabricated concrete panels, windows, doors, structural steel elements and roof structures. For the charge weights and distance combinations examined, the relevant blast parameters appear to be peak overpressure and pressure risetime. It appears to be possible to produce damage charts for each element involved which give the probability of percentages of damage as a function of peak pressure at the incident shock wave. However, additional information and new data is needed for further verification. It is also recognized that other aspects, such as induced groundshock and dangers for human beings that are hit by fragments of damaged structural elements, are also important in a hazard analysis.

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LIST OF SYMBOLS

W	charge weight
R	distance
t_+	positive duration
P_{so}	peak side - on pressure
T	natural period
$F(t)$	load function
x	displacement
x_v, x_u	yield and ultimate displacement
$\hat{F}/kx_v = \bar{F}$	dimensionless peak value of the loading
$t/T = \bar{t}$	dimensionless time
t_d	duration of the loading
$D_u = x_u/x_v$	ductility ratio
t_p	risetime, of the loading
P_{bs}	static pressure causing buckling of a compression arch
E	Young's modulus
h	thickness of the wall panel
R'	radius of the compression arch

1. INTRODUCTION

Recently, a new method of analyzing and judging dangerous situations and activities such as in traffic, transportation of LNG, storage of explosive goods, etc. has been developed. This method is called risk analysis, and the main objective of this method is to examine the effect of a failure in these situations or activities as well as the probability that such an event will happen. In a recent contract, the TNO-PML laboratory has performed a study of the hazards involved in the storage facilities of explosive materials. In particular, the project team studied the risks for people living near or passing by an ammunition storage area^{(1)†}.

Fig. 1 is an example of a damaged storage building and Figs. 2 and 3 are examples of these hazardous situations. From the photos, one can visualize the problems which can arise in the Netherlands--that is, roads and habitated buildings near explosion hazards. Until now, there have not been accidents in the aforementioned situations, but accidents have occurred with old World War II charges, with other disapproved charges, and in propellant production facilities. Fig. 4 is an example of such an accident and gives a map of recorded damage caused by an explosion in a propellant plant. Before going into the details of the damage estimation, explanation will be given on other items that have been investigated and the overall scheme in which they are placed (Fig. 5).

Concerning structural damage, there exists a need to know, as a function of some blast parameter, the probability that a certain kind of damage to a structure or structural element will occur. For example, a structural element like brickwork will have a low probability of complete failure in a blast field with incident peak overpressure of 15 kN/m^2 but will have a high probability of minor damage (such as cracking) in the same blast field. To illustrate the meaning of different damage percentages Figures 7, 8 and 9 are added which give varying brickwork damage. Figures 10 and 11 are illustrations of corrugated steel and reinforced concrete failures.

† Superscript numbers in parentheses designate References at end of paper.

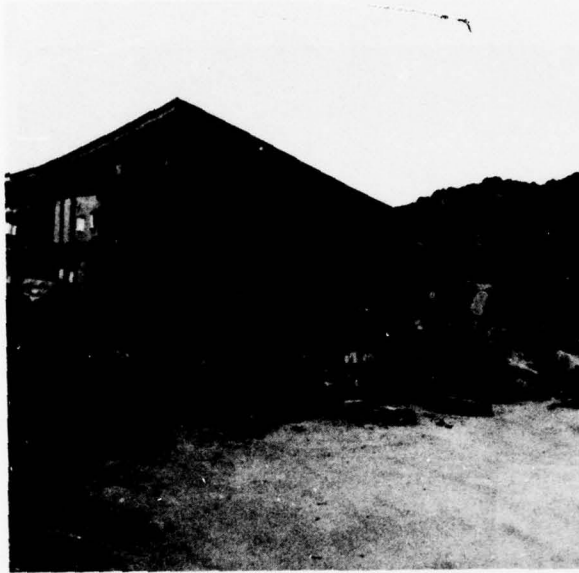


Figure 1. Damaged storage building of explosive goods.
(Arch no. 780821)

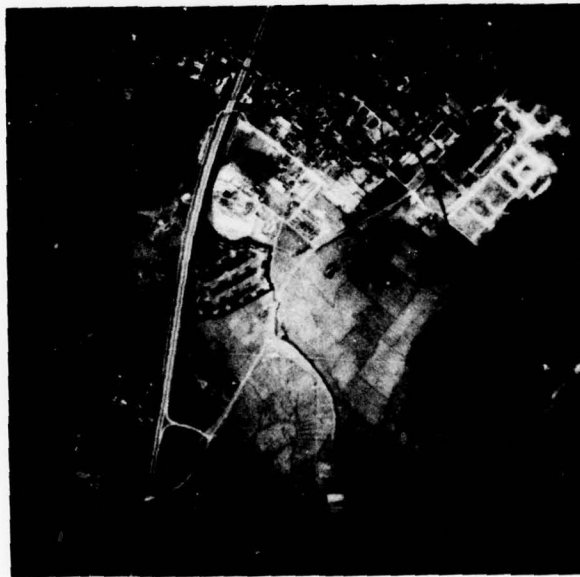


Figure 2. Example of a hazardous situation: ammunition storage near a highway and an urban area. The circle represents the required safety distance according to NATO regulations. (Arch no. 780819)

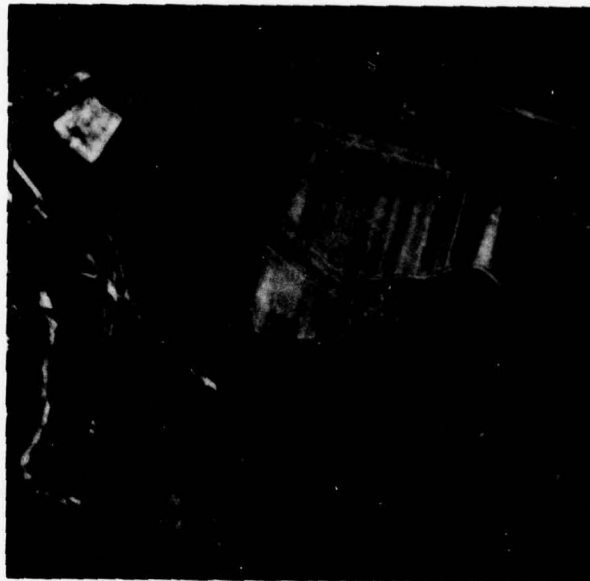


Figure 3. Example of a hazardous situation: ammunition storage near to one of Holland's major canals. The circle represents the required safety distance according to NATO regulations. (Arch no. 780817)

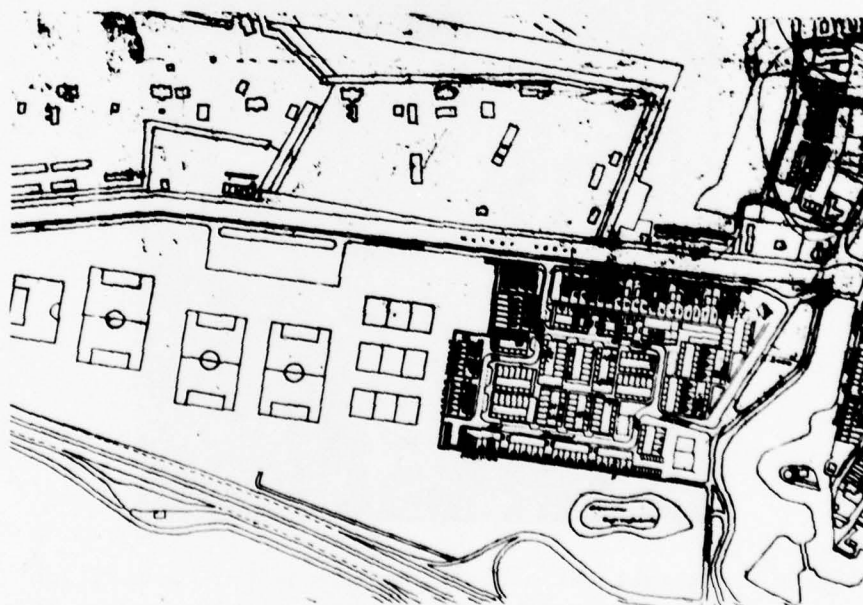


Figure 4. Map of reported damage caused by an explosion in a propellant plant. The cross is the explosion center, black spots are registered damages. Notice the soccer fields for scale. (Arch no. 780822)

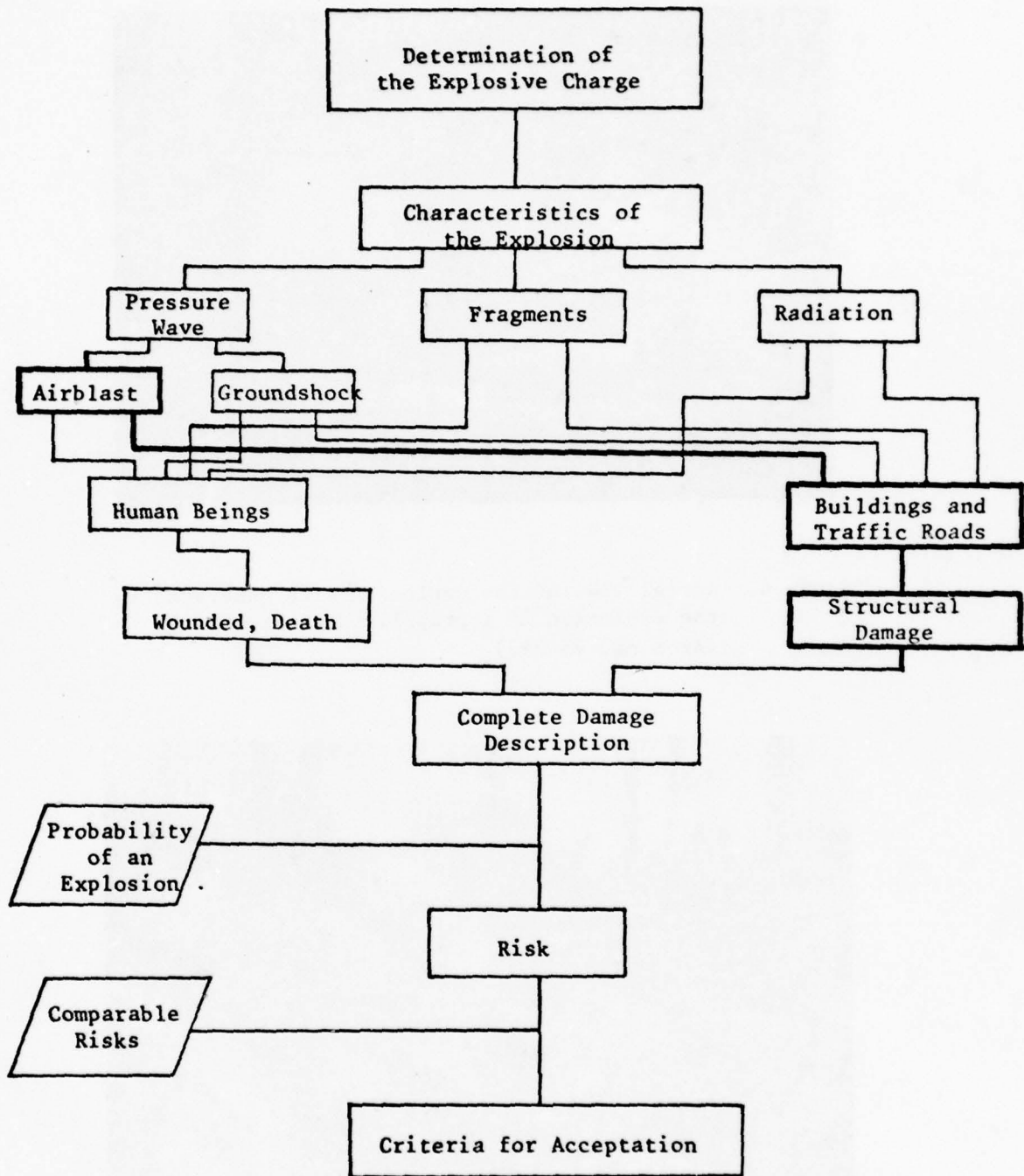


Figure 5. Overall scheme of the performed risk analysis.



Figure 6. Aerial view of the explosion site generated by the explosion in a propellant plant.
(Arch no. 750297)



Figure 7. Example of brickwork damage: complete demolition.
(Arch no. 740937)

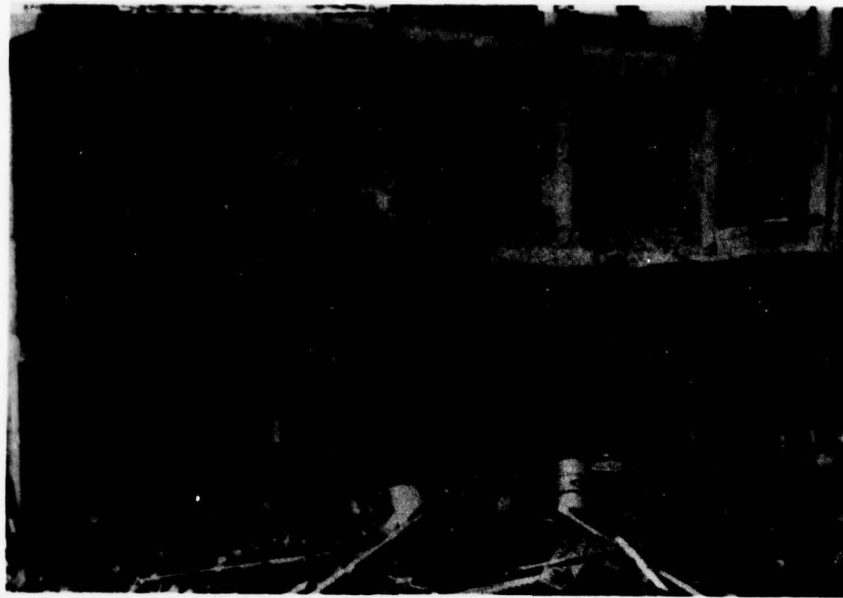


Figure 8. Example of brickwork damage: major parts blown out. (Arch no. 750372)



Figure 9. Example of brickwork damage: cracking. (Arch no. 780820)

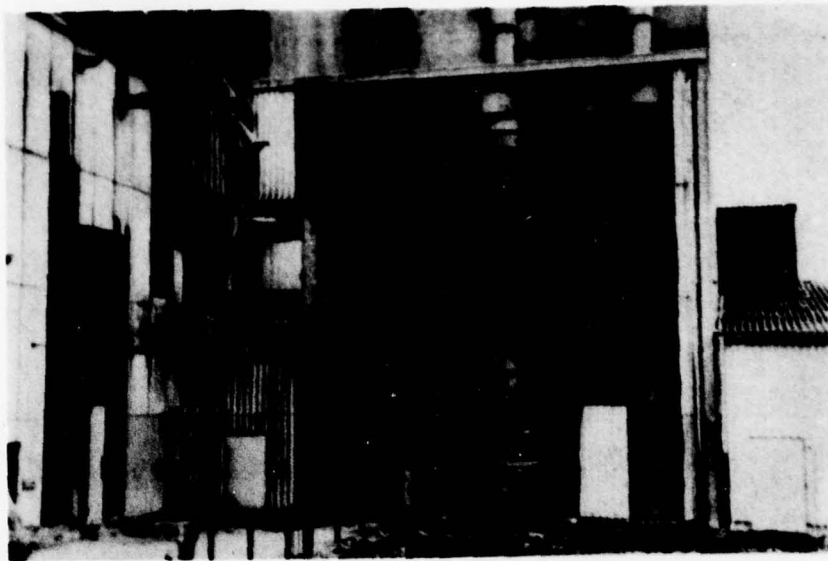


Figure 10. Example of damaged corrugated steel plates.
(Arch. no. 750830)

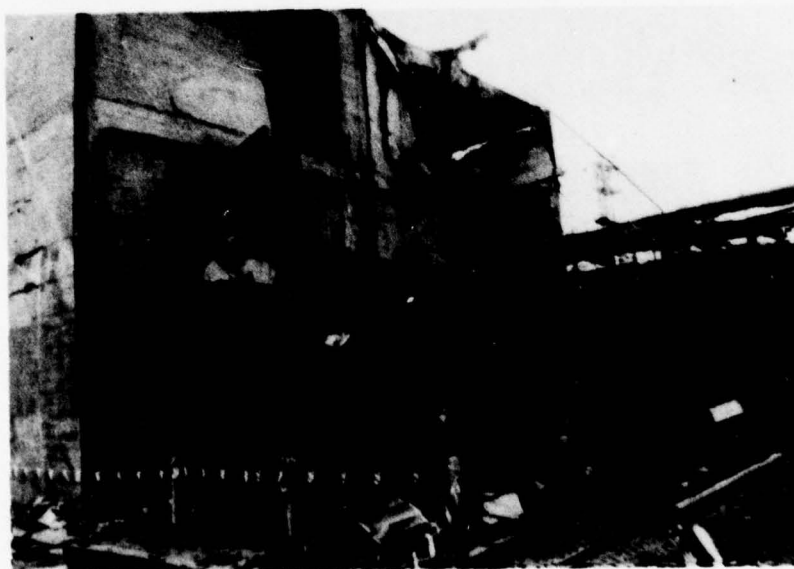


Figure 11. Example of damaged reinforced concrete slabs.
(Arch no. 760306)

II. URBAN STRUCTURES IN RELATION TO EXPLOSION HAZARDS

As previously mentioned, consideration has been given in this study to the effect of an explosion of stored explosives in the vicinity of urban structures. Urban structures in the vicinity refers to residences, flat apartments, and farm houses at distances of 1000 m or more. Not all of these structures are composed of a load bearing main structure containing other structural elements such as curtain walls, glass panels in steel frames, etc. In fact, most of these structures consist of load bearing walls with structural elements such as brickwork partition panels and prefabricated concrete front panels. For the estimation of damage, considerable attention should be given to the behavior of the structural elements.

One can make a significant simplification when studying the behavior of structural elements and building frames loaded by shock waves coming from an explosion of the kind considered in this report. While the equivalent TNT charge weight of these kinds of explosions varies from 10,000 to 40,000 kg and the distance from 300 to 500 m, it can be derived⁽²⁾ that the minimum value of the positive phase duration will be 0.16 sec. That is, for $W = 40,000$ kg and $R = 300$ m:

$$E = 1.8 \times 40,000 \times 4.516 \times 10^6 = 3.25E11 \text{ Nm}$$

$$\bar{R} = R \sqrt[3]{P_o/E} = 300 \sqrt[3]{1E5/3.25E11} = 2.025$$

$$\bar{T}_s = 0.365 = T_{s_o} \sqrt[3]{P_o/E}$$

$$t_+ = \bar{T}_s/a_o \sqrt[3]{E/P_o} = 0.365/340.3 \sqrt[3]{3.25E11/1E5} = 0.16 \text{ sec}$$

The durations are relatively long compared to the short response times of the structural elements being considered. In the following section, the

influence of this large t_+/T ratio will be derived by means of a theoretical model and other blast wave characteristics which determine the response of the structures and the possible damage will be investigated.

Other aspects that have to be taken into account are reflection as a function of angle of incidence and the actual loading on the structure composed of loads at the front and back side of the structure in which building dimensions and shock wave speed are important parameters. Because these aspects are sufficiently described in handbooks, they are not further treated here.

III. STRUCTURAL DYNAMICS

As stated previously, the influence of the t_+/T ratio and other blast characteristics such as waveform and rise time will be examined by means of the simplest calculation model available--a single degree of freedom model⁽³⁾.

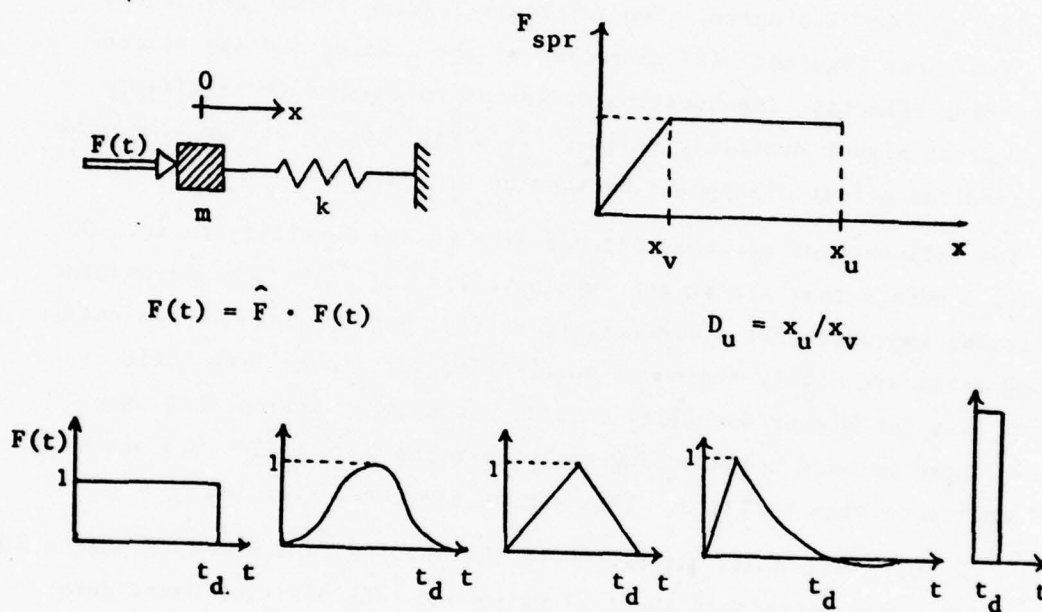


Fig. 13 - Single degree of freedom model with possible load functions

The differential equation that describes this problem is:

$$m \frac{d^2x}{dt^2} + kx = F(t)$$

which becomes:

$$\frac{d^2\bar{x}}{d\bar{t}^2} = 4\pi^2 \{F(\bar{t}) - \bar{x}\} \text{ for } 0 \leq \bar{x} < 1/\bar{F}$$

$$\frac{d^2\bar{x}}{d\bar{t}^2} = 4\pi^2 \{F(\bar{t}) - \bar{x}_v\} \text{ for } \bar{x} \geq 1/\bar{F}$$

by substitution of: $\bar{t} = t/T$, $\bar{x} = x (k/\hat{F})$, $\bar{F} = \hat{F}/kx_v$ ⁽⁵⁾.

By numerical solution, the displacement $\bar{x}(t)$ can be found and can be related to the ultimate displacement ⁽⁴⁾.

In Fig. 14, combinations of peak value $\hat{F}/kx_v$ and duration t_d/T are shown for these load functions which produce a maximum displacement equal to the yield displacement: $D_u = 1$. Fig. 15 gives the same result plotted in the well known PI diagram. Two important loading parameters become clear from these figures: (a) rise time of the loading and (b) periodical loading effects. The question arises as to whether these effects also occur at higher ductility ratios. From Fig. 16, it can be seen that the periodical effect disappears as soon as $D_u > 3$.

The influence of risetime depends also on the ductility ratio. Obviously, loadings that are in the impulsive loading realm are independent of risetime influence for all ductility ratios; but loadings in the static loading realm are highly dependent on risetime for a ductility ratio of one and less for higher ductility ratios. Newmark ⁽⁵⁾ states that when $D_u > 2$, there is only a 10% influence by risetime when $t_p/T < 0.5$ and only a 30% influence when $t_p/T < 3$. This can be seen from Fig. 17.

For this particular study, where the loading is assumed to have a shock wave shape with infinitely short risetime and long positive phase duration, it appears that the critical parameter for damaging structural elements is the peak value of the applied load. Comparison can be made with the static design loading taking into account reflection with a reflection coefficient of about 2 and infinitely short risetime giving a dynamic load factor of 2.

- = block shaped load
- = sinusoidal load
- ▲ = triangular load
- ▲ = typical blast wave load

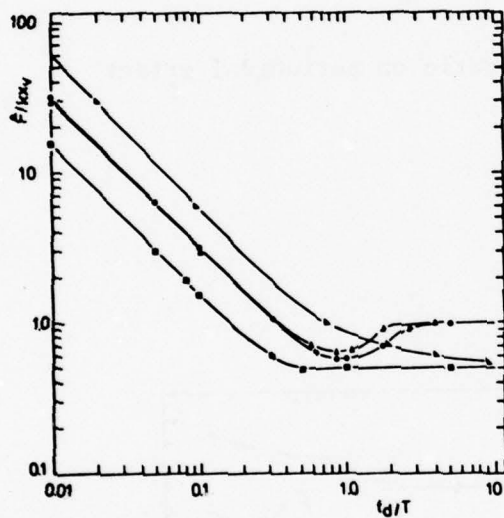


Fig. 14 - Combinations of peak value and duration producing D_u ratio equal to one
(Arch.no. 780823)

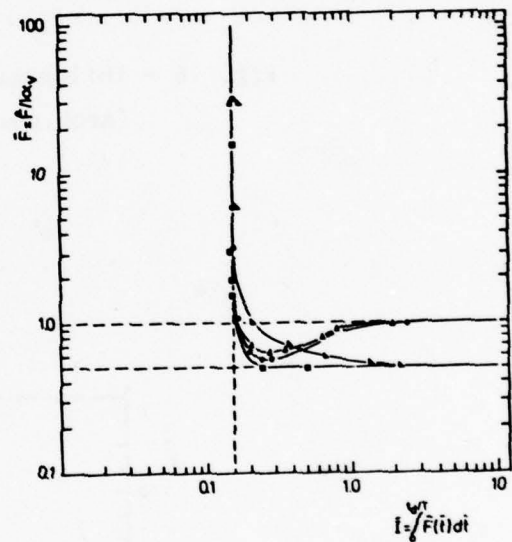


Fig. 15 - P.I. diagram of loadings producing D_u ratio equal to one

(Arch.no. 780824)

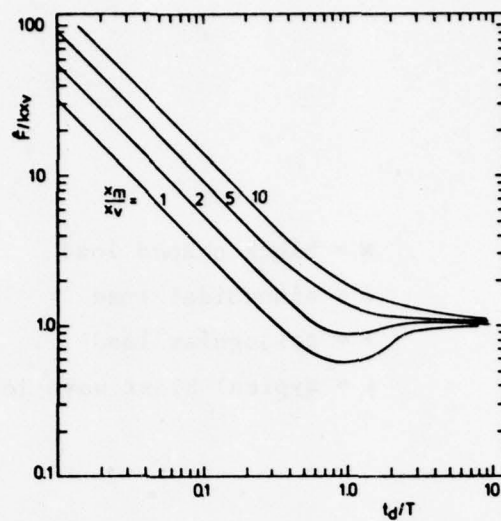


Fig. 16 - Influence of D_u ratio on periodical effect
(Arch.no. 780825).

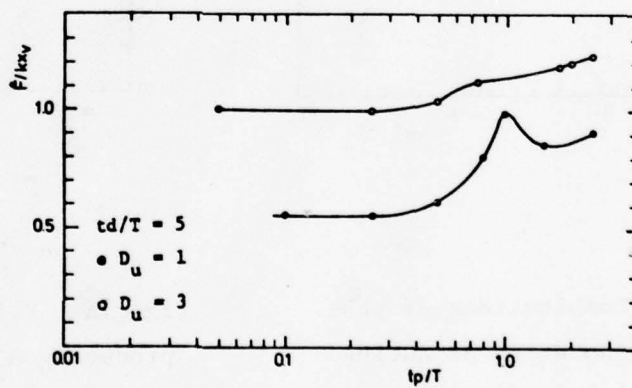


Fig. 17 - Influence of risetime on required
resistance at several D_u ratios
(Arch.no.780826)

IV. PROBABILITY OF DAMAGE

As previously mentioned in the introduction, the need exists to know as a function of a blast parameter (such as peak overpressure) the probability that certain kinds of damage to an element will occur. Fig. 18 is an illustration of this need. As far as we know, only one reference gives probabilities of damage, based on a comprehensive study⁽⁶⁾. This work of Pickering and Bockholt of SRI is only partially usable for this study because the building types are different and because a probability is given for only one kind of damage. For instance, they give the probability of 75% damage to roof structures of several kinds of buildings.

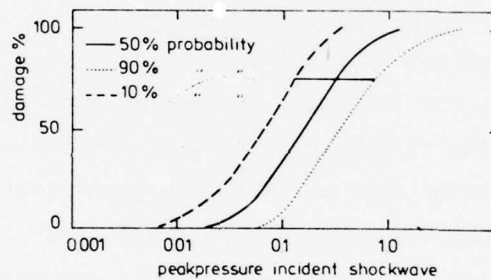


Fig. 18 - Damage probability diagram
(Arch.no.780827)

Another source for this study has been the several papers presented at previous Explosive Safety seminars giving results of explosion tests on structures where the blast field and damage have been recorded⁽⁷⁾. Also, test results of wall panels in blast simulators such as the ones reported by Wilton, Gabrielson, and Kaplan for URS Research Company have been used⁽⁸⁾. Finally, an estimation has been made of upper and lower boundaries; that is, 100% probability of complete demolition and 0% probability of no visible damage. The last boundary can be related to design loads such as wind, taking into account load factors.

V. AIRBLAST DAMAGE CHARTS

As far as possible, these data have been used to make damage charts for the structural elements considered. These were: concrete and brickwork walls, corrugated steel and asbestos cement plates, roofs, windows, and doors because these elements will occur in most of the urban areas encountered. Damage curves for the aforementioned structural elements appear in Figs. 19 through 24. The author does not propose that the entire damage description can be made exactly by means of these charts. Nevertheless, any estimation better than rules, such as those shown in Table 1, is worthwhile. The charts contained in this paper are not yet complete. Extensions must be made for other elements and more data should be obtained for a better foundation of these charts.

The problems that arise when processing the available data can be illustrated by considering brickwork damage. Distinction must be made between load bearing and non-load bearing walls. After restriction to non-load bearing walls, the thickness becomes an important parameter: 11 cm, 22 cm, or two 11 cm walls with 6 cm spacing. Then for a 22 cm wall, data are available⁽⁹⁾ with which one must estimate the appropriate percentage of damage and probability of damage represented by a description like "slight cracking and deflection." In Table 2, the result of this estimation is given for 22 cm brick panels with no openings. In Fig. 25a, these values are plotted in the damage-probability diagram. A lower boundary can be estimated from a wind loading⁽¹⁰⁾ of 1.0 kN/m² which makes $P_{so,0\%} = 0.45 - 0.50$ kN/m² with a low probability. An upper boundary can be estimated with the following formula which is derived for buckling of a cylinder⁽¹¹⁾ (Fig. 26)

$$P_{bs} = 0.861 (Eh^2/R'L) \sqrt{h/R'}$$

where, in this case, the cylinder is formed by the compression arch in the wall panel. This leads to the upper boundary for $P_{so,100\%}$ of 45 kN/m² and 200 kN/m² for wall heights of 3.6 and 2.4 m, respectively. These values are given in Fig. 25b.

- Δ ◇ = solid brickwork, 8"
- ◆ = solid brickwork, 4"
- = brickwork, 4" and 8" concrete blocks with 2" spacing
- = probability for all load carrying brickwork walls
- = probability for panel and curtain walls
- ▲ = probability for panel and curtain walls with no openings

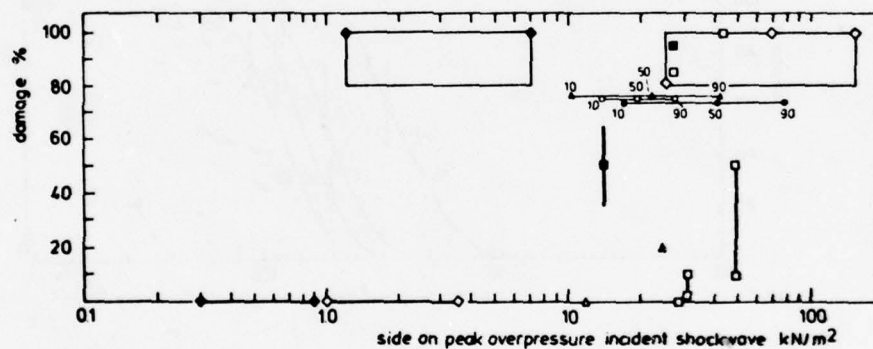


Fig. 19 - Damage chart, brickwork
(Arch.no.7709102-3)

- ◇ = wall, thickness 0.15 m
- △ = wall, thickness 0.20 m
- = panel, thickness 0.20 m
- = wall, thickness 0.25 m
- ✦ = wall, thickness 0.30 m

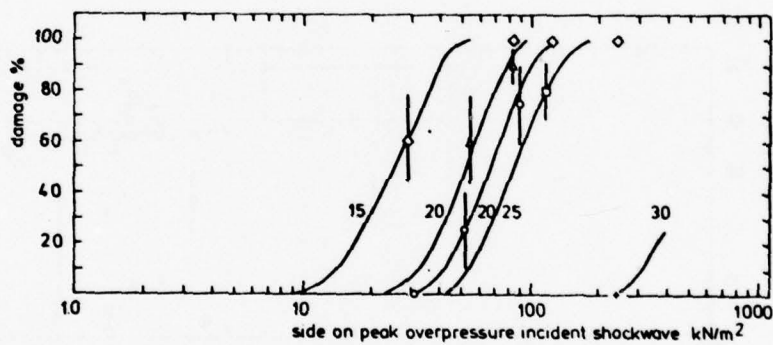


Fig. 20 - Damage chart, concrete walls
(Arch.no. 7709103-3)

- = probability of damage for corrugated panels
 of steel and asbestos cement
 Δ = corrugated steel
 □ = asbestos cement panels

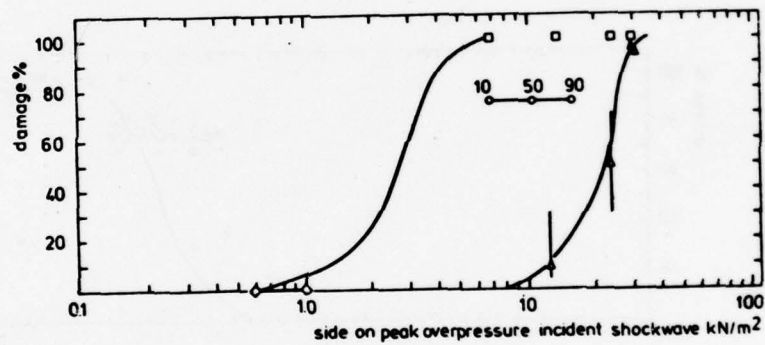


Fig. 21 - Damage chart, corrugated panels
 (Arch.no. 7709104-3)

- = probability of 75% damage, peaked wooden roof with tiles
- △ = probability of 75% damage, flat roof built up
- × = probability of 75% damage, flat concrete roof
- = wind loading

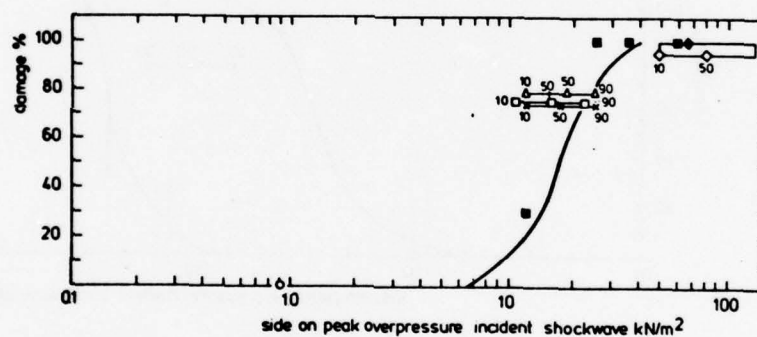


Fig. 22 - Damage chart, roof structures
(Arch.no.780828)

- ◇ = btheta distribution function, residences⁽⁶⁾
- = btheta distribution function, flat apartments⁽⁶⁾
- × = btheta distribution function, tall office buildings⁽⁶⁾
- △ = tall office buildings⁽⁹⁾
- = residences⁽⁷⁾
- = wind loading

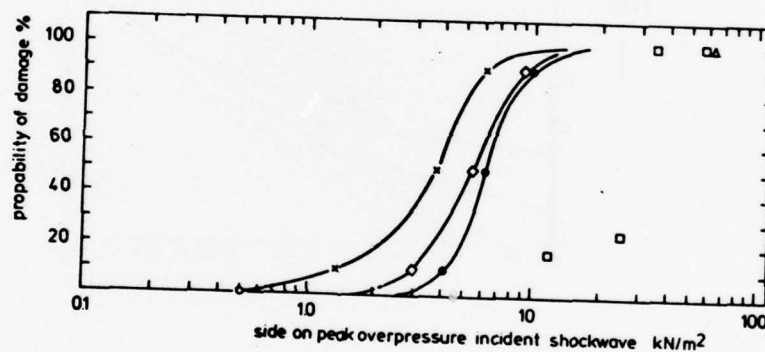


Fig. 23 - Damage chart, doors
(Arch.no.780829)

- , o = data based on analysis of accidental propellant explosion using different explosive yields
- ◇ = data from I. W. Reed, Explosive Safety Seminar 1973
- + = data based on analysis of accidental propellant explosion in 1963
- x = TNO experiments on window panes

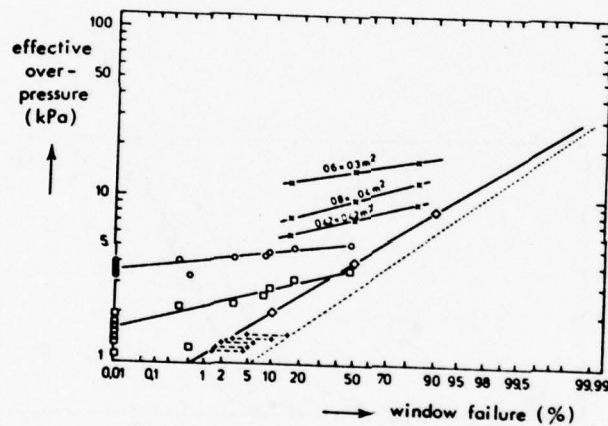


Fig. 24 - Damage chart, glass panels
(Arch.no.7709105-D)

- = test data on 8" brickwork walls.
- △ = estimated upper boundary from buckling
- = bheta distribution for a 75% damage
- ◇ = data from experiments
- ▲ = estimated lower boundary from wind loading

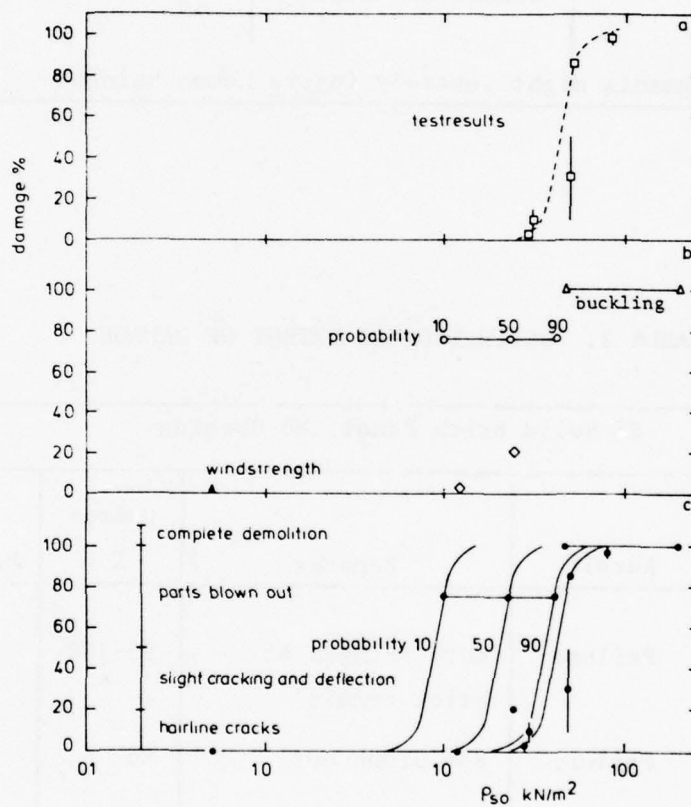


Fig.25. Generation of a damage chart by gathering all available data.

(Arch.nos. 780830-A, 730837-B, 780838-C)

TABLE 1. DAMAGE RULES

Damage Table Department of the Interior	Zone I	42 kN/m ²
	Zone II	14 kN/m ²
	Zone III	7 kN/m ²
Damage Table TNO/CTI	Badly Damaged	$P_{so} = 30 \text{ kN/m}^2$
	Repairable Damage	$P_{so} = 10 \text{ kN/m}^2$
	Window Breakage	$P_{so} = 3 \text{ kN/m}^2$

Fragments might severely injure human beings.

TABLE 2. ESTIMATION OF EXTENT OF DAMAGE

8" Solid Brick Panel, No Openings					
P_{so} kN/m ²	P_r kN/m ²	Result	Remarks	Damage %	Probability
83	223	Failure	only fringes of brick remain	95-100	
52	127	Failure	85% blown out	85	
50	119	Damage	slight cracking and deflection	10-50	
31	70	Damage			
31	70	Undamaged	some spilling	5-15	
29	65	Undamaged	almost damage-free, hairline cracks	0-5	

As mentioned earlier, Pickering and Bockholt give probabilities of 75% damage to brickwork panels, curtain walls, or load-carrying walls for several kinds of buildings. For exterior walls with no openings, these values are:

10% probability for at least 75% damage, $P_{so} = 10.2 \text{ kN/m}^2$

50% probability for at least 75% damage, $P_{so} = 24 \text{ kN/m}^2$

90% probability for at least 75% damage, $P_{so} = 42 \text{ kN/m}^2$

Figure 25c is the final result where all the data points are gathered and correlated to each other.

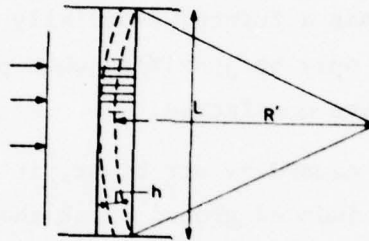


Fig.26.

(Arch.no. 780831).

VI. CONCLUSIONS AND FUTURE DEVELOPMENTS

Considering the previous material and facts, the only justified conclusion that can be drawn is that there must be some relation between damage caused by the blast wave and the probability that this damage occurs for each structural element. The relations that have been given in the previous text should be handled with great care. We feel that additional data are required to make them more general and give them more validity. Moreover, a very careful elaboration of old and new material should be made; and the relations presented above should not be handled as some kind of standard and completed guidance but as an approach of estimating and judging damage to urban structures caused by explosions. Yet, we believe that this approach has a future, especially in the Netherlands, where many activities can only be justified when probabilities of unwanted events and their effects are considered.

Besides the damage caused by air blast, it became clear recently that the damage caused by induced ground shock should not be neglected. Analyzing damage caused by an unconfined vapor cloud explosion in Beek, the Netherlands, it became obvious that the damage that occurred to a certain school building was not caused by air blast directly but by the induced ground shock. Other references^(12,13) stated that damage to buildings in the region where air blast can be neglected can be caused by ground shock. Another development for the future may be that in civil engineering sciences, a probabilistic approach may become popular and will enable us to calculate probabilities of failure, incipient failure, minor damage, and no visible damage. Since this study is not yet completed and will not be completed in the near future, we feel that a call for information, references, data, and critics is the best approach. Possibly, a data bank on this subject can be set up which would work with defined approaches and judging rules.

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