SOME CONSIDERATIONS ON THE DAMAGE CRITERIA AND SAFETY DISTANCES FOR INDUSTRIAL EXPLOSIONS

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The empirical criteria presently used to determine structural damage due to explosion effects are very rough. This makes it impossible to go to a more detailed and reliable level in risk analysis.
Analytically derived pressure impulse diagrams are presented showing the sensitivity of the amount of damage for a variation of structural and blast load parameters. This emphasizes the need for a better of understanding of the phenomena involved.
Examples of research efforts are presented to determine blast loadings on structures in different situations.

INTRODUCTION

Due to the enormous growth of potentially hazardous industrial activities and the transportation of dangerous goods, the risk to which society is subjected grows considerably. Knowledge of the physical effects of the technological hazards becomes very important in order to perform accurate calculations and predictions with the help of consequence analysis. For each of these effects, detailed information of all relevant aspects is necessary as the accuracy of the analysis is determined by the depth of knowledge on each aspect.

Three main successive areas can be distinguished to model the effects of for instance an explosion:
- the source of the explosion from which a certain explosion strength can be derived
- the propagation of the effects away from the source, the interaction with and the load imposed on structures and humans
- the response of structures and humans to the load.

At the end of a risk analysis one is interested in the amount of damage and injury to be expected from a certain source, or in the opposite direction in the case of damage analysis, one is interested in the source strength. However, in spite of all the efforts that, hitherto, went into the modelling of explosion effects, parts of the second area and certainly the third area are still underdeveloped. Fortunately, the interest for damage and injury criteria is growing as it is realized that the present situation is not satisfactory.

In The Netherlands this situation was recognized and as a follow up of the so called "Yellow Book" (1), with which the physical effects of the accidental release of dangerous goods can be calculated, the so called "Damage Book" (2), named after its contents, or "Green Book", named after its color, was published by the government. With the methods in this book the effects to humans and structures due to the physical effects, determined by the Yellow Book, can be calculated.

However if one tries to go more into detail, one soon will be encountered with questions about the actual load on structures and about the actual response characteristics of the structures themselves. And, it appears that the analytical modelling becomes more and more important apart from the empirical methods used so far.
Some of the related aspects will be enlighted in this paper. Partly, this will be done by a parameterstudy with a simple dynamic response model. Although most of the aspects relate to both humans and structures, emphasis is put on the latter.

DAMAGE CRITERIA

The calculation of explosion damage is mainly based on empirically derived criteria. With the help of tables, which give a more or less rough description of the damage to certain types of structures for each increment of the level of overpressure, damage circles are drawn. An example of such a damage table is presented in Table 1.

TABLE 1 - Damage to be expected for certain levels of overpressure.

Pressure (kPa)	Damage
1	Typical pressure for glass failure
2	Some damage to ceilings
3	Limited minor structural damage
7	Partial demolition of houses, made uninhabitable
15	Partial collapse of roofs and walls of houses
20-30	Rupture of oil storage tanks
50	Collapse of steel girder framed buildings
70	Complete destruction of all unreinforced buildings

Although there is no problem to extend the table, it will be clear that the information remains rough and that it is difficult to obtain any information on specific situations.

Additionally, one has to realize the sources with which these tables were compiled. Data came from damage observed during bomb attacks, experiments with enormous amounts of high explosives and from observations on experiments with and applications of nuclear weapons. It is striking to see the correspondence between for instance the damage tables given in Glasstone and Dolan (3) which were first derived in the late Forties and tables like Table 1. During the years, these damage versus overpressure relations were applied for all kinds of circumstances which differed largely from those for which they were derived. It can be expected that other explosive sources than nuclear or high explosions, for instance gas deflagrations or chemical and physical explosions will have different effects on structures. Furthermore, construction methods and materials are not similar in all continents; not even within countries; construction methods and materials have changed and were developed further during the past years. Other damage effects can be expected for these situations.

In spite of all these differences, the damage criteria live their own lives. Because they are applied in both risk analysis and damage analysis for all kind of situations, loops are created for which the link to reality is difficult to distinguish. This is surely valid in situations where other than high explosive detonations are expected, for instance, the chemical industry.

An objection against the application of damage overpressure relations is the disregard of the blast duration which is important in dynamic analysis. It is quite simple to demonstrate the differences in damage to be expected for blast waves with similar levels of overpressure but different durations.

Fortunately, this phenomenon is recognized more and more and the effect is discounted in the damage-overpressure relations. Table 2 (taken from Merrifield (4)) for instance relates damage classes, applied in the UK, to different levels of overpressure depending on different quantities of TNT. As the blast duration for larger TNT quantities is longer, pressure levels for which a certain damage occures, are lower.

TABLE 2 - Damage levels depending on overpressure and TNT quantity.

Damage category	Approximate peak side-on overpressure (kPa) for different TNT quantities (kg)		
	1000	10.000	100.000
D	5	3	3
C_a	12	8	8
C_b	28	17	16
B	80	36	35
A	180	80	76

Brief damage description:

D : Damage to ceilings and tilings, minor fragmentation effects on walls and window panes

C_a : Minor structural damage, reasonably repairable, wrenched partitions and joints

C_b : Partial or total collapse of roof, partial demolition of external walls, severe damage to load bearing parts

B : Damage to houses is beyond repair, 50 to 70 % external brickwork demolished

A : Houses completely demolished

A more appropriate presentation of the influence of the duration on the damage level is the so called pressure-impulse diagram. The impulse, the integrated time function of the overpressure, is a measure for the duration. To each overpressure and TNT quantity a certain value for the impulse belonges. The advantage of this approach is that pressure and impulse determine the level of damage without a TNT equivalence concept. Pressure impulse diagrams were derived by Baker et al. (6) with the relation of Jarret:

$$R = \frac{K.W^{1/3}}{(1+(3175/W)^2)^{1/6}} \qquad (1)$$

which combines amounts of explosives W and distances R at which a certain level of damage occurs for variable values of K.

It is interesting to note that during the derivation of Equation (1) which was meant for estimating damage to UK dwellings due to bombs during World War II, it was at first assumed that the impulse would be responsible for the damage and not the overpressure (Cantrell (5)). In addition to this it must be noted that the reference also states that the equation is valid for bombs with an explosive weight of about half the total weight. The effect is that a large portion, say 50 per cent of the available energy is transferred into the fragments kinetic energy. Consequently, the blast will be less than in case of a bare charge and the damage is underestimated. Apparently, this restriction was lost somewhere in the darkness of history as damage calculations based on TNT equivalence models do not account for this aspect.

Figure 1 gives the pressure impulse diagram of Baker. Curves in the Figure combine pressure impulse combinations for which a certain described damage level occurs.The vertical asymptote is called *Pressure* asymptote, since pressure determines damage; horizontally is the *Impulse* asymptote. Pressure impulse combinations lying above and to the right of an iso-damage curve will cause higher damage levels. The influence of the blast duration is very clear, as for lower values for the impulse, the pressure can increase without causing more damage.

A path in the figure can be drawn for each amount of high explosives quantity, usually expressed in kg TNT, which gives the pressure impulse combinations for all distances. For the far (infinite) distance the path starts at the origin (0,0) and the closer the distance to the source, the higher the values for pressure and impulse. To assess by means of the P-i diagram the possibility of damage as a function of distance given a certain charge, following the corresponding path from the far field both asymptote values of impulse and pressure have to be crossed for a certain damage to occur. For small quantities, the impulse extreme is the last one to be crossed and is therefore decisive.

Included in Figure 1 are results from trials mentioned in (3). The accompanying figures refer to the percentage of the total building costs needed to repair the damage. For all these results, the overpressure was decisive, as large amounts of explosives were used.

Although the pressure impulse diagram is a good tool to obtain feeling for damage levels, it can be misleading if the restrictions for its applications are neglected. It must also be kept in mind other parameters can have an influence that besides positive overpressure and positive impulse. This will be demonstrated in the next section

PRESSURE IMPULSE DIAGRAMS

Although impulse is recognized as an important parameter besides the overpressure, with the help of the empirical criteria, no distinction can be made for different situations. What is the influence of blast waves with shapes differing from the shapes of high explosive blast waves; what is for instance the influence of a large negative phase typical for a bursting pressure vessel, or the influence of a certain rise time, typical for a gas explosion? And what is the influence of obstacles on the propagation of the initial shock wave and what effects do they have on the resulting dynamic loading on a structure within a group of structures?

As empirical data is lacking, an analytical approach of the problems might give some answers. It appears to be possible to produce analytical pressure impulse diagrams with iso-damage contours. Both the load and the structure have to be modelled for this. As an example, pressure impulse diagrams will be presented here for the dwellings for which the empirical pressure impulse diagram of Figure 1 was derived.

Let us assume that the structure can be modelled into a single degree of freedom system, the simplest dynamic system. Besides the mass, the stiffness and the horizontal static ultimate load of the structure, some definition of damage is required. For this we assume an elastic-plastic behaviour. Up to the ultimate load, the structure will sustain no damage and the behaviour will be elastic. For higher loads, the structure will not collapse but will deform plastically. The ratio of the total deflection, elastic plus plastic, and the maximal elastic deformation, defined as the ductility ratio (Du) is then a measure for the amount of damage. In the pressure impulse diagram, iso-ductility curves will then represent iso-damage curves.

Dimensionless pressure impulse diagrams can be derived where the dimensionless pressure is the ratio of the peak pressure (P) in the blast and the static horizontal ultimate load (P_{st}) of the structure and with a dimensionless impulse consisting of the impulse (i) of the blast wave times the circular frequency (ω) and divided by the static ultimate load (P_{st}) of the structure.

For the comparison with the empirical diagram, real values of the structural parameters have to be derived. Taking a typical Dutch house, these values can be calculated.

In reference (2) it was stated that a typical value for the natural frequency (f) is 5 Hz ($\omega = 2.\pi.f = 31.4$ /s). The mass will be in the order of 50.000 kg. With the single degree of freedom system the horizontal stiffness is calculated at about 50 MN/m. The wind load for which low structures have to be designed for is approximatly 1 kPa. As the real ultimate load will be higher, the value for P_{st} is chosen here as 2.5 kPa. The loaded area is taken as 100 m^2.

To model the load, let us first assume a very simple shape, for instance the triangular shape with zero rise time. This shape is often assumed for rough blast response analysis as a schematization of the actual incident shape. It must be realized that the actual shape of the load can differ considerably due to reflection, rarefaction and expansion effects or due to an internal pressure development as the blast enters the structure.

Determination of the ultimate deflection with a single degree of freedom calculation for each pressure impulse combination yields Figure 2A. The values for the ductility ratio were chosen to coincide as much as possible with the iso-damage contours of Figure 1. It appears that in the impulse region (small impulse, large pressure) where the response is determined by the impulse, it is possible to fit empirical and analytical results. In the pressure region it is impossible to coincide ductility and damage curves as the extreme for all ductility ratios is 0.5 times P for the assumed load.

A parameter study can be performed in order to find out what the effect is on the shape of the *iso-ductility curves. A total study however would lead much to far, as for each combination of* time function of the load and stiffness characteristic of the structure, a different dimensionless diagram can be composed. Therefore we will restrict ourselves to some interesting variations.

The variation of structural parameters will be considered first.

VARIATION OF STRUCTURAL PARAMETERS

The first uncertainty is the static ultimate load (P_{st}). Just one value for the structure as a whole seems incorrect as window panes are expected to fail at a lower pressure than the masonry walls. A value of 2.5 kPa seems too low in comparison with the empirical diagram as damage starts in the pressure region at 1.25 kPa. However, higher values than 10 kPa are unrealistic, as damage in the form of window pane breakage already occurs at a lower level. The result for the diagram (Figure 2A) in case of a higher ultimate load, will be a shift of the vertical lines to the right.
The choice of the natural frequency is also open to discussion. Figure 3, taken from Adeli (7), shows actual measured natural periods T ($T=1/f$) of dwellings. A factor of two in variation can occur easily.

Figure 2B shows the pressure impulse diagram for the case where P_{st} is changed to 10 kPa and f to 20 Hz. The frequency of 20 Hz follows from the stiffness calculated for the assumed structure of the dwelling of the example. This is in contrast to the previous example where the frequency was taken as the initial parameter. The ductility ratios were chosen to fit the empirical curves of Figure 1. As both ultimate load and stiffness were increased, the influence in the impulse region is minor. The result is that damage in the pressure region is expected to occur at higher pressure levels.

Another question is the actual ductility ratios of structures. For brittle parts such as window panes, the ductility ratio will be 1 (unity). For the other structural parts the ratio to be applied still remains uncertain. From earthquake studies, ductility ratios of 4 can be found for concrete structures although then very minor damage is expected. At the state of failure, values of ductility ratios between 10 and 20 seem more appropriate. These values are fairly well in agreement with the values chosen in the example.

The last question raised here is on the plastic stage of the response. Depending on the structural design and the applied materials, the horizontal branch of the stiffness characteristic can change in either an increasing branch (steel) or a decreasing branch (concrete, masonry), which will have its effect on the required ductility ratios and the shape of the iso-ductility curves. It will be clear that for each response characteristic of the structure different diagrams can be composed.

The results so far show that it is possible to choose realistic combinations of the structural parameters to obtain analytically derived damage levels consistent with actual observations. At this point, the variation of the load parameters can be started.

VARIATION OF LOAD PARAMETERS

First the triangular shaped wave with zero rise time is extended with a negative phase in which the underpressure is 0.25 times the peak overpressure with a duration of 4 times the positive phase duration. Now, we have a wave with similar positive and negative impulse values. Figure 4 is included to show that these values are realistic. The pressure was measured at a distance of 44 m from the explosion of about 300 m^3 methane. Figure 2C gives the pressure impulse diagram. The influence of the negative phase is restricted to the impulse region. The pressure region and, remarkably, the transition zone are not affected at all. The influence in the impulse region is clear as for very short load durations the applied impulse on the structure is zero, so no damage is expected regardless the overpressure.

The second variation is the introduction of a certain rise time. This is the time during which the pressure increases from zero to its maximum value. Here the rise time was taken as half the positive phase duration. The shape of the negative phase was taken similar to the shape of the positive phase but with opposite sign. An example is shown in Figure 5 which was taken from Wickens (8). The signal comes from experiments by British Gas on Bleves of Butane filled vessels. The combustion of the evaporated liquid shows the blast wave with a rise time of half the positive phase duration and with a large negative phase.

It can be questioned whether the schematization is correct as the wave is preceded by other waves which are able to produce damage also. The preceding waves consist of: the blast from the detonating explosive to rupture the vessel, the blast from the expanding vapor and the blast from the vaporating liquid.

In case no combustion takes place, the remaining wave is typical for a bursting gas filled vessel: two pulses with a relatively very large negative phase in between. This shape will have a different damaging effect than the shape for which Figure 2A was derived.

Figure 2D shows the pressure impulse diagram for the schematized load. Due to the chosen rise time, the iso-ductility lines in the pressure region shift to the right. The pressure asymptote is now equal to the peak pressure of the load. This means that the pressure at which a certain damage occurs is twice the level for a wave with a rise time of about zero. This will reduce the damage radius considerably as for lower pressure levels the reduction of pressure with increasing distance is rather small.
This specific blast shape has no influence in the impulse region.

BLAST LOADING ON STRUCTURES

As was demonstrated in the previous section, the pressure impulse diagram is a very suitable tool to get a feeling for the influence of different shaped blast waves and different structural response characteristics on the amount of damage to be expected. However, the situation becomes more complicated when a closer look is taken at the total response. Three aspects will be discussed in this section:

- structural failure during the negative phase of the response
- the influence of the structure on the applied blast load
- the influence of other structures on the applied blast load.

The aspects will be enlightened by results of the research efforts performed at the TNO Prins Maurits Laboratory.

Structural failure during negative phase of response

The given diagrams assume that the damage will occur due to the movement of the structure in the direction of the pressure. In fact, a structure will vibrate with a movement opposite to that direction also. In case the structure is weaker in opposite direction or the movement is accelerated due to a negative loading phase it is possible that the structure collapses during this negative vibration phase. The following example will demonstrate this.

For the determination of the resistance of window panes against blast loads a blast simulator is often applied. The pane is then mounted to the exit of the simulator and is loaded with successive shock waves with increasing peak overpressure, until the pane fails. It appeared very often that the fragments after the failure were lying inside the simulator. High speed film demonstrated that the panes failed during the negative vibration phase. Figure 6A shows a reflected pressure signal as measured on the plane in which a window pane was mounted to a 2 m diameter blast simulator.

Figure 6B shows the calculated deflection of a window pane with dimensions $1.2 \times 1.2 \times 0.005\ m^3$, modelled to a single degree of freedom system. Here, similar stiffnesses were taken for both positive and negative vibration phases. It appears that the negative deflection, opposite to the direction of the blast, is larger then the positive deflection. The negative movement is strengthened by the negative load phase. A consequence is that the pane seems stronger when it is loaded with a peak overpressure which is larger than the experimental failure load of the pane.

Influence of structure on the applied blast load

Another complication is that the actual load on a structure or on a structural member can greatly differ from the shape of the incident blast wave.

Methods in literature can be found to model the applied dynamic load on a structure due to the interaction with a blast wave. Effects of reflection, rarefaction and expansion can be taken into account. However, it is always assumed that the structure is fully closed. In reality, openings are always present. Then, the blast can enter the structure and load the structural members from the inside. This influences the resulting dynamic load on for instance the walls of a house. It is not difficult to imagine that the internal pressure supports the walls, which can therefore withstand higher pressure levels.

To investigate the influence of openings on the resulting blast load, a chamber was placed at the exit of a 2 m diameter blast simulator. The blast wave could enter the chamber through an orifice with variable dimensions. Experiments were performed with open orifices and orifices closed by window panes. A model could be derived from the results to determine the resulting dynamic loads on the walls. Figure 7 shows the influence of the orifice. The net load for the fully closed chamber is given for the front wall by the dashed line in situation 1A (Figure 7) and for the side wall, situation 2A (Figure 7) gives the net load. The difference with the fully closed structure is obvious. During a certain period of time the resulting load is even directed outwards. With this result in mind it is not remarkable to find that walls fell outwards during blast trials on full scaled houses.
The test with window panes showed a remarkable result. Although the panes failed within a few milliseconds, it took almost the entire positive phase duration of the blast wave applied, to create the full opening. The result of this was that almost no blast could enter the chamber.

Very few references are known on the influence of adjacent obstacles or structures on the resulting blast load on a structure within a group of structures. This is remarkable as one can imagine that the shielding effect of one structure to another reduces the pressure load on the latter. On the other hand, the load on the rear of a structure could be enlarged by extra reflections from a structure downwind. The outcome of a study on these effects could be a reduction of the iso-pressure circles around explosion sources and a reduction of damage radii in connection.

To show the influence of multiple structures a numerical example was made. Figure 8 shows a *two dimensional fluid flow calculation of a shock wave passing two boxtype structures.* The incident shock wave had a peak overpresure of 10 kPa and a positive duration of 10 ms. A negative phase was included also. Figure 8A shows the iso-pressure lines at different points of time. Reflection, rarefaction and expansion effects can be distinguished. Figure 8B shows the pressure transients at different locations. Transient 4 shows the pressure on the front of the second structure. In comparison with transient 1, for the pressure on the front of the first structure, a remarkable reduction was obtained. However, comparing the transients 3 and 6, extra reflection increase the load on the rear of the first structure. Naturally, this is just one example. Experiments and parameter studies will have to be performed in order to quantify pressure distributions in real situations.

CONCLUSIONS

The present empirical damage criteria for explosions only give a rough insight into the level of damage to be expected. They cannot be applied in situations where small quantities of explosives are involved. They certainly can not be applied in cases where the blast wave characteristics differ from those of high explosive detonations, for instance if a certain rise time or a considerable negative phase is present, as is the case with gas deflagrations or pressure vessel bursts.

The application of analytically determined pressure-impulse diagrams is a useful tool to investigate the variation of blast and structural parameters on the damage to be expected.

Possibilities exist to obtain detailed insight into damage levels with these analytical diagrams, but then the information of the actual load applied on the structure and the response characteristics must also be known in detail. Certainly, this will require a great deal of research effort, but with the knowledge gained it will be possible to differentiate between distinct various situations.

Some important aspects are: the influence of openings in a structure and the influence of adjacent structures on the total dynamic load, and the deformation capacity of structures themselves.

SYMBOLS USED

Du = ductility ratio (-)

f = natural frequency (Hz)

i = impulse (Pa.s)

H = height (m)

K = factor for determination of damage radii ($m.kg^{-1/3}$)

L = length (m)

M = mass (kg)

P = peak overpressure (Pa)

P_{st} = horizontal ultimate load (Pa)

R = distance (m)

T = natural period (s)

W = amount of explosives (kg TNT)

ω = circular frequency (s^{-1})

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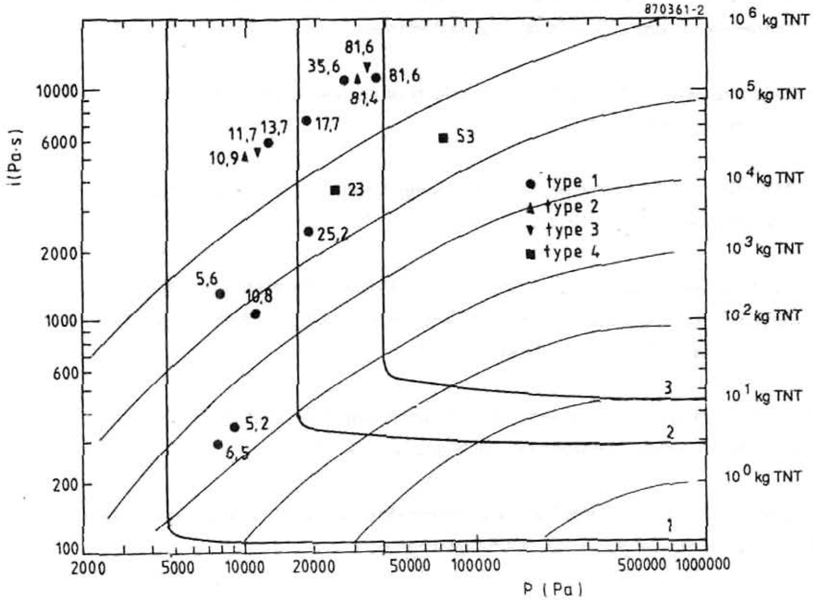
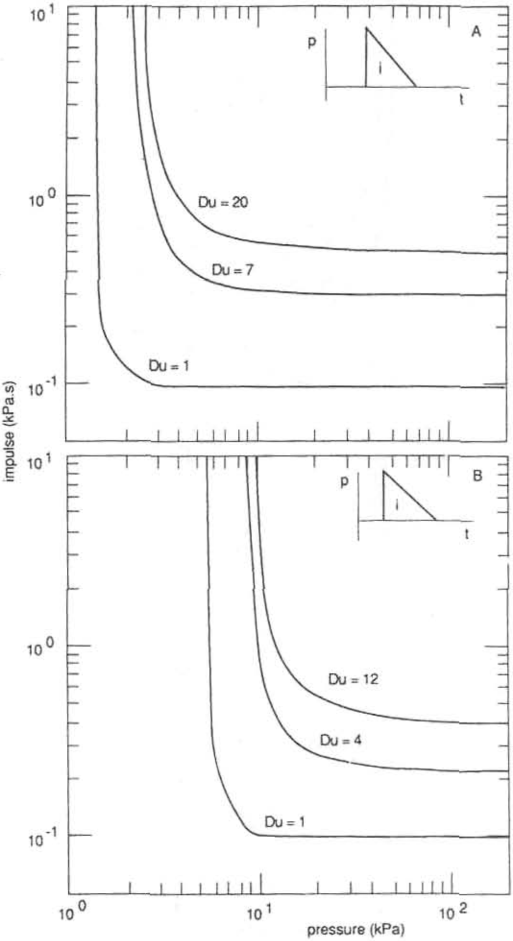


- Iso-damage curves:
  - -1 Treshold for minor structural damage
  - -2 Treshold for major structural damage
  - -3 Treshold for partial demolition
- Experimental results on houses, numbers refer to percentage damage of total building costs.

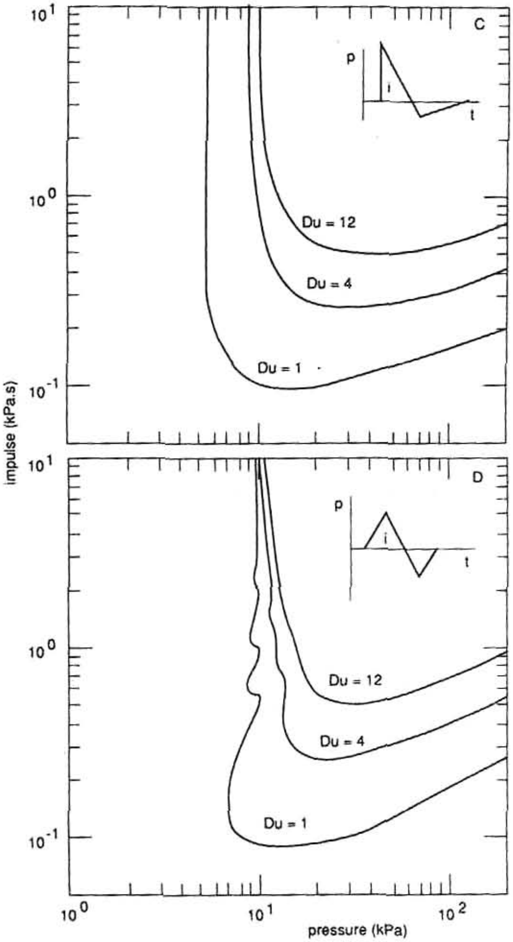
  Types: -1 two floor wooden house
  - -2 two-floor masonry house
  - -3 single-floor wooden house
  - -4 two-floor masonry house
- Incident pressure impulse path for different amounts of explosives.

Figure 1 Pressure-impulse diagram for dwellings



A: f = 5 Hz, P_{st} = 2.5 kPa,
M = 50000 kg, K = 49.3 MN/m
triangular blast wave with zero rise time

B: f = 20 Hz, P_{st} = 10 kPa,
M = 50000 kg, K = 780 MN/m
triangular blast wave with zero rise time



C: f = 20 Hz, P_{st} = 10 kPa,

M = 50000 kg, K = 780 MN/m

Blast wave extended with negative phase

D: f = 20 Hz, P_{st} = 10 kPa,

M = 50000 kg, K = 780 MN/m

triangular blast wave with rise time and negative phase

Figure 2 Calculated pressure impulse diagrams for elasto-plastic single degree of freedom schematization

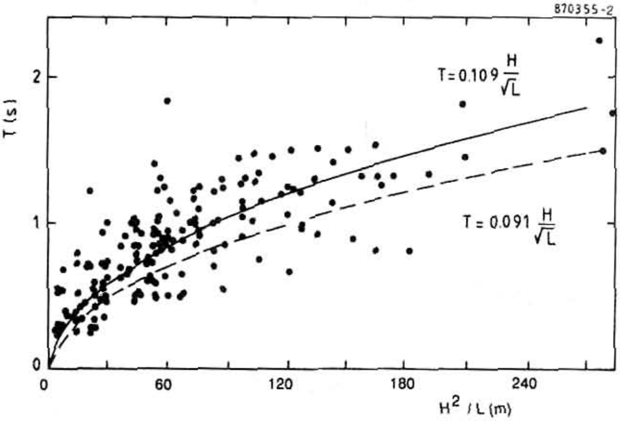


Figure 3 Variation of natural periods of houses as a function of H^2/L

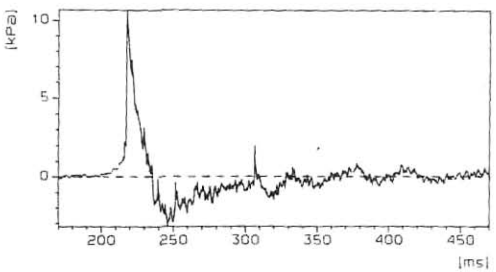


Figure 4 Pressure measured at a distance of 44m from a 312.5 m^3 methane explosion

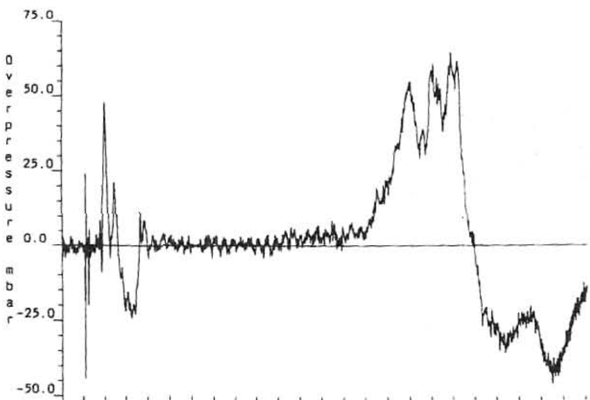
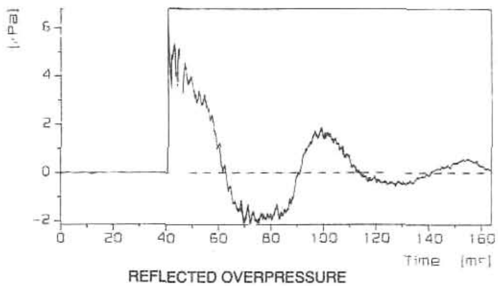
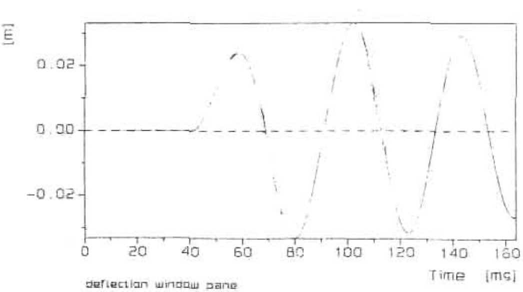


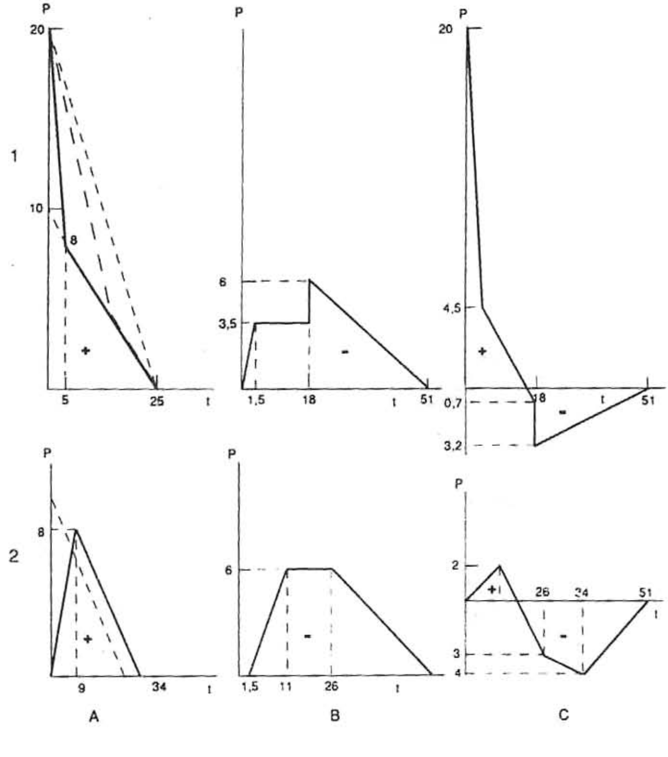
Figure 5 Pressure measured at a distance of 25 m from a Bleve of a butane filled vessel with a volume of 5.6 m3





A: reflected pressure on window pane
B: calculated mid-point deflection

Figure 6 Window pane response to blast load



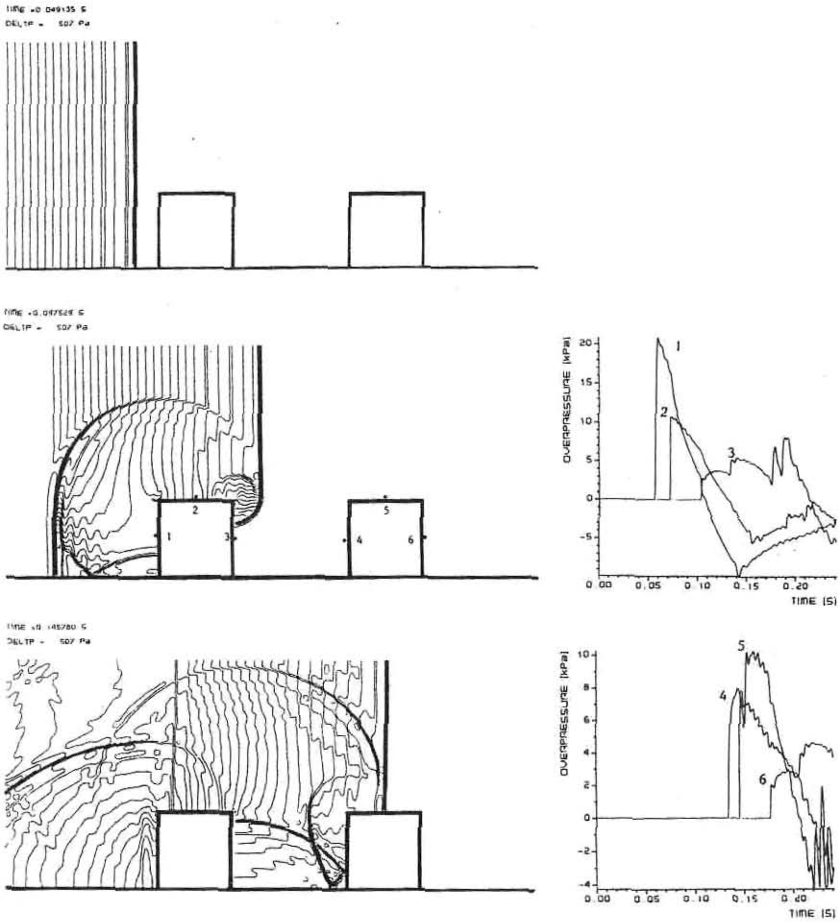
1: front wall, 2: side wall

A: external load, B: internal load,

C: resulting load

+: pointed outwards, -: pointed inwards

Figure 7 Schematized average resulting loads on walls of structure. Dimensions in kPa and ms



A: pressure distribution at sequential points of time

B: pressure transients at different locations

Figure 8 Numerical calculation of interaction of blast wave with two structures