

Rxxx

Response Spectra for Explosion Resistant Design and Assessment

Introduction

This paper describes a project performed by Atkins (MSL) to examine the explosion test results obtained at Spadeadam in the 1990's from the point of view of structural response. BP supplied the FLACS simulated pressure traces corresponding to the experimental results obtained at Spadeadam. The technical reviews by the HSE were performed by Roland Martland.

The main objective of the project was to derive static design pressures for sizing main structures and barriers. The spectral response method also provides a robust method of comparing the severity of simulated and experimental pressure traces than can be derived from consideration of peak pressure alone.

Structural design engineers are often presented with complex simulated or experimental pressure traces and are expected to design efficient structures to resist the explosion scenarios they represent.

It is usually desirable to allow significant local plastic deformation in order to arrive at an efficient design. This often results in the need for a non-linear, dynamic design approach which may be expensive and can be prone to error. Plastic deformation is quantified in terms of the ductility, defined as the maximum deformation divided by the deformation at the yield point [1,2]. The allowable ductility is limited by the function of the structural element considered and the nature of its connections to the surrounding structure.

The Response Spectrum approach brings the explosion response checks within the framework of a conventional design or modification project. The information needed to apply the method is an estimate of the natural period of vibration of the target structure 'T' and its allowable ductility ' μ '.

The static resistance capacity of the target structure 'R' is defined as the resistance at effective yield [1,2].

The response spectrum approach has been in use for decades in the earthquake response context and was in fact pioneered in the Second World War to calculate ground motion effects and structural response from explosions [3].

The Response Spectrum approach is illustrated by reference to the Prototype Biggs response method [4] which is familiar to most explosion resistant structure designers.

Actual experimental and simulated pressure traces have also been used to generate a set of specific response spectra corresponding to each pressure trace. These response spectra have been averaged to give preliminary 'Generic' response spectra which may be used, particularly at the early stages of Design. The idealised triangular pressure traces have some characteristics which are not present in general for more irregular experimental and simulated traces.

The load is represented by the load duration 'td' and the effective pressure 'Pe', defined below.

Spadeadam tests – experimental pressure traces

A large number of full scale explosion tests were carried out at the Spadeadam test site in the UK between 1990 and 2002. These explosion events were also simulated using the Computational Fluid Dynamics (CFD) predictive code FLACS [5]. Direct comparison of simulated and experimental pressure time histories has been inconclusive.

The measured pressure traces contained a large number of short duration 'spikes' superimposed on a generally smooth curve, of a form similar to the typical pressure time history shown in Figure XXX.1.

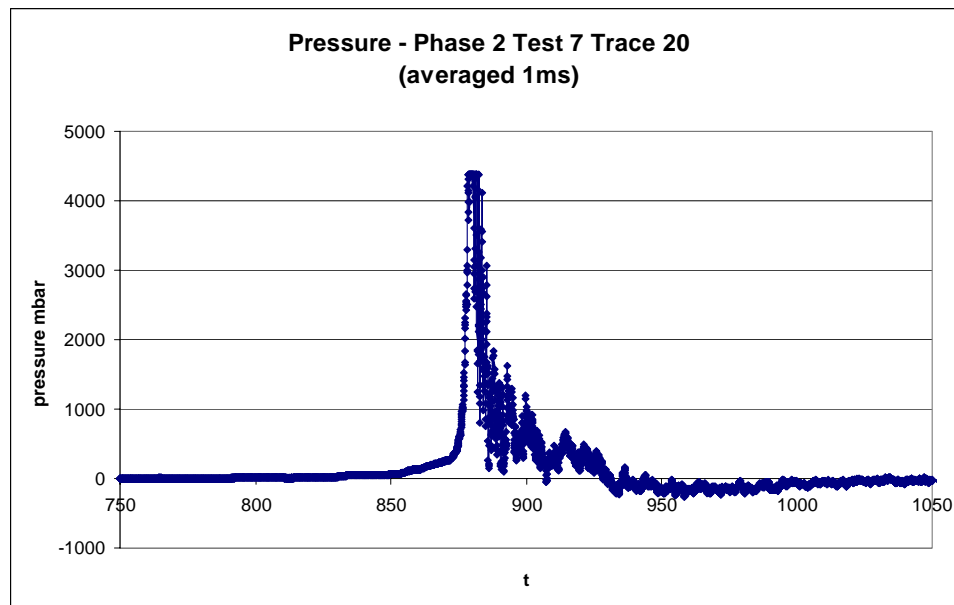


FIGURE XXX.1 Typical pressure time history from experiment

Whatever the cause of these spikes, investigations have shown that the influence of these short duration loads is insignificant for structural components with natural periods more than 0.02 seconds (natural frequency less than 50 Hz) - which includes most components. Simulations are not able to resolve these spikes and they do not appear on the simulated pressure traces.

These spikes, which can easily take the observed peak overpressure P_{peak} beyond 12 bar, make P_{peak} an unreliable measure of explosion severity.

Representation of load severity.

Impulse, defined as the integral under the pressure trace, is an important parameter for explosion structural response and it includes all the data in the positive phase of the pressure-time history. There is also a more consistent correlation between impulses for actual test results and CFD simulations.

One approach to deriving the effective pressure P_e and the load duration which is tailored towards actual experimental and simulated traces is illustrated in Figure XXX.2. This method was originally presented in reference 6.

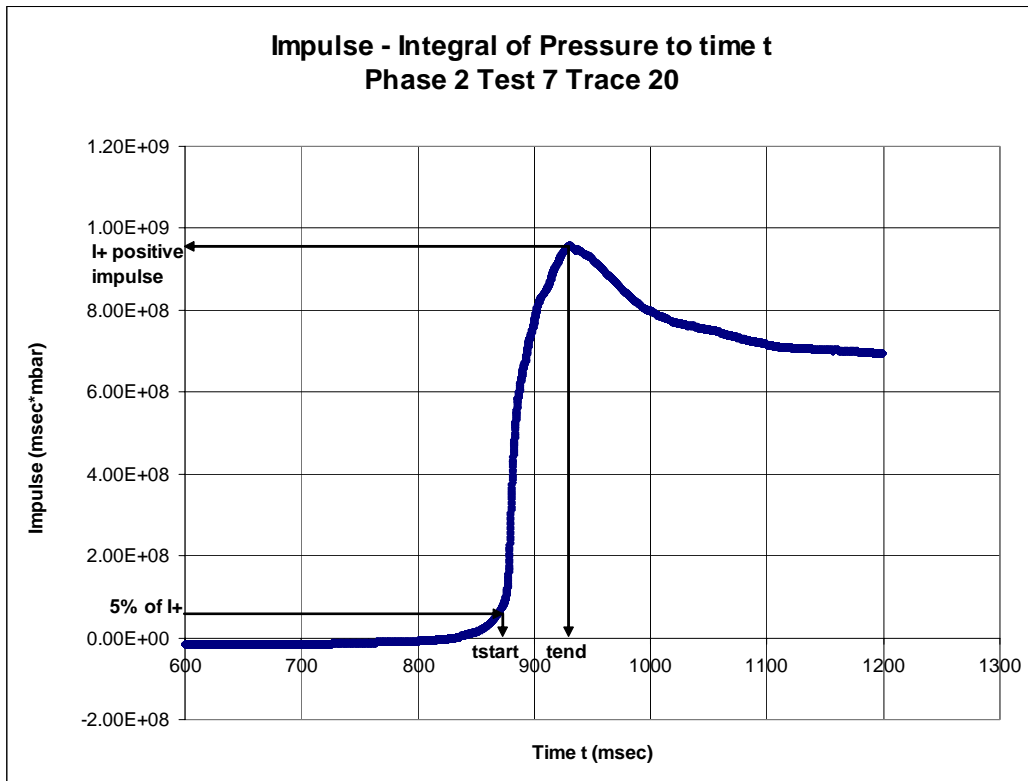


Figure XXX.2 Method for Calculation of Duration and Positive Impulse for an Irregular Pressure Trace

The graph shows the accumulated impulse to time t for a realistic pressure trace similar to that shown in Figure XXX.1. The ‘spikes’ in the original curve are smoothed by the process of integration and do not appear in the graph.

The start time of the pressure pulse ‘ t_{start} ’ is assumed to be the time at which the positive impulse reaches about 5% of the peak value. This is because pressure traces often have an extended lead phase where the pressure is negligible whilst the explosion is developing.

The time at which the pressure trace effectively next crosses the axis is given by the time of maximum impulse ‘ t_{end} ’ on the graph.

These times may be extracted and the difference may be taken to be the load duration ‘ td ’.

The effective peak pressure P_e may then be calculated directly from the positive impulse using:-

$$I^+ = \frac{1}{2} td \times P_e \quad \text{or} \quad P_e = \frac{2I^+}{td}$$

This effective pressure P_e has been found to be a good measure of explosion trace severity and has been found to be the parameter which enables generic response spectra to be derived.

It is easily related back to the prototype Biggs formulation where the peak and effective pressures (P_{peak} and P_e) are in fact identical.

Response surfaces

The derivation of a response surface for a triangular load time history is illustrated in Figure XXX.3.

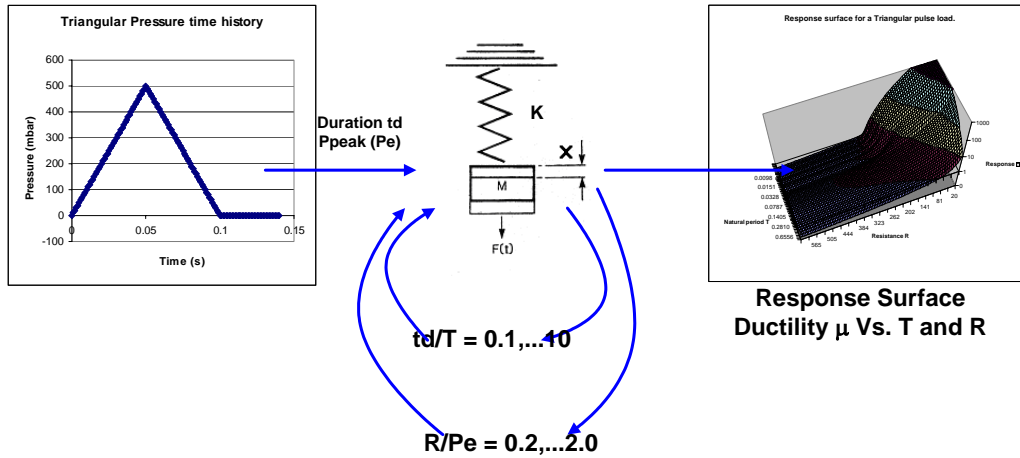


Figure XXX.3 Generation of Response Surfaces (Biggs load idealization)

The response surface, for a triangular load time history is shown in Figure XXX.4. The horizontal axes are the natural period 'T' and the resistance 'R'. The vertical axis is the peak deflection corresponding to the values T and R in the ranges considered and is expressed in terms of the ductility 'μ' at peak displacement.

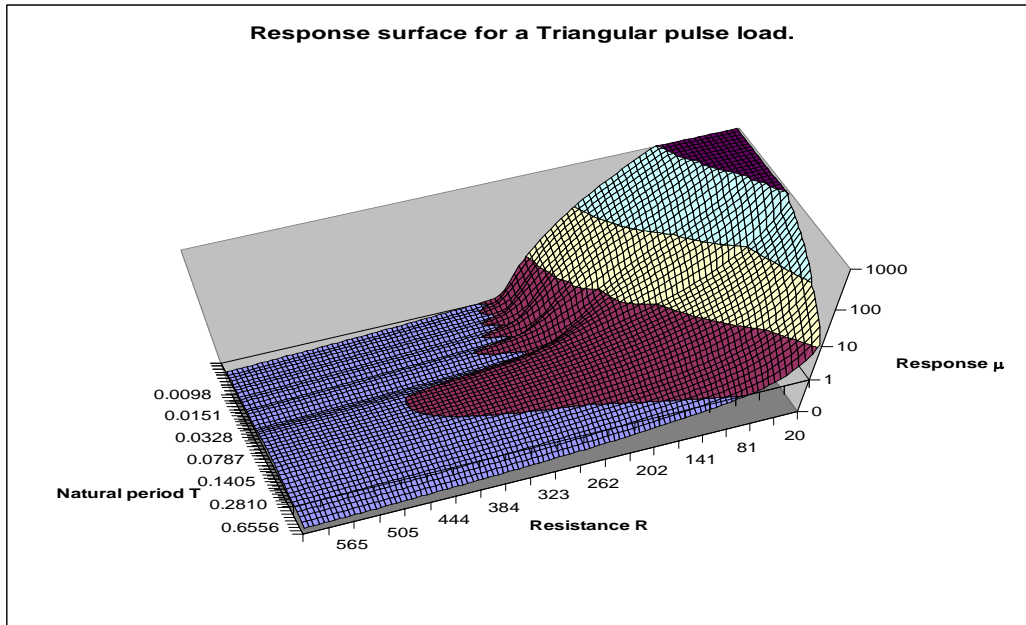


Figure XXX.4 Response surface for a triangular pressure time history

In general, where the magnitude of a response is determined by two variables, say X and Y, then the relationship between these two variables at fixed (desirable/allowable) levels of response may be plotted using a response surface representing the response for ranges of X and Y. The extension to more than two variables is trivial.

Example of the use of response spectra

Referring to Figure XXX.6:-

If the structure has natural period of 50 msec and the load has a duration of 100 msec then td/T is 2.

For a structure with an allowable ductility of 2 the curve corresponding to $\mu = 2$ should be used.

R/P_e is then 0.85. For a triangular load time history with effective pressure equal to 1000 mbar. The required static resistance 'R' is then $1000 \times 0.85 = 850$ mbar. This structural element may then be tested against an applied static load of 850 mbar to see if it fails the code checks at this load level.

This process is illustrated in Figure XXX.7 below.

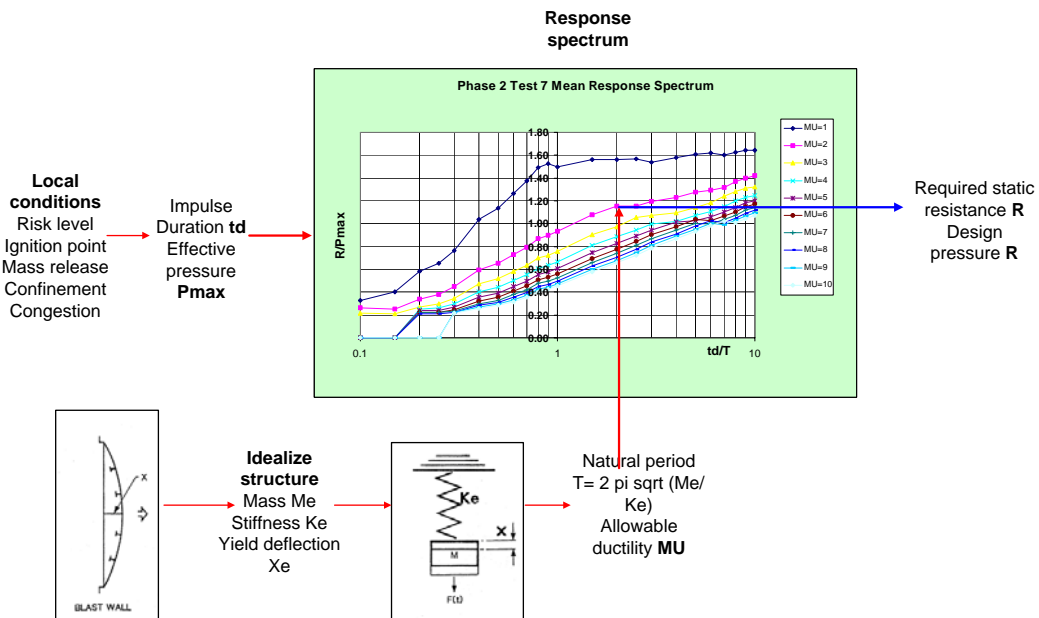


Figure XXX.7 The use of response spectra to determine equivalent static loads

Mean Response Spectra

Structural elements to be assessed may be panels, decks, modules or whole topsides if they can be idealised as a one degree of system non-linear spring mass system. This process will be familiar to designers who use the Biggs response method [3] and is in routine use.

Figure XXX.8 gives Response Spectra obtained by averaging all Response Spectra for all sensor measured pressure traces and for all tests in the Phase 2 Spadeadam full scale explosion experiments.

Actual test and simulated traces were used to generate response surfaces corresponding to each sensor point in the Phase 2 tests using the method illustrated in Figure XXX.2. A mean response spectrum calculated using all the Phase 2 Spadeadam test pressure traces is given in Figure XXX.8. The resistance scaling used for the idealised triangular load time histories has been found to be suitable for test and simulated traces of general shape.

Each pressure trace was run through the response calculation for 23 natural periods chosen to give td/T ratios in the range 0.1 to 10. The traces were each run for each natural period and for 100 structural resistances. This yielded a response surface with 2,300 points for each trace.

The data examined included:-

Phase 2 tests – 27 tests each with about 20 measurement positions giving about 500 traces.
Phase 2 simulations – 27 simulations. The first 20 traces for each simulation were run through the response calculations.

Response Spectra were calculated for allowable ductility values from 1 to 10.

The construction of these response spectra involved in excess of 3,000,000 sets of response calculations. The responses were then averaged for each test and over all the tests. The corresponding simulated data was processed in the same way.

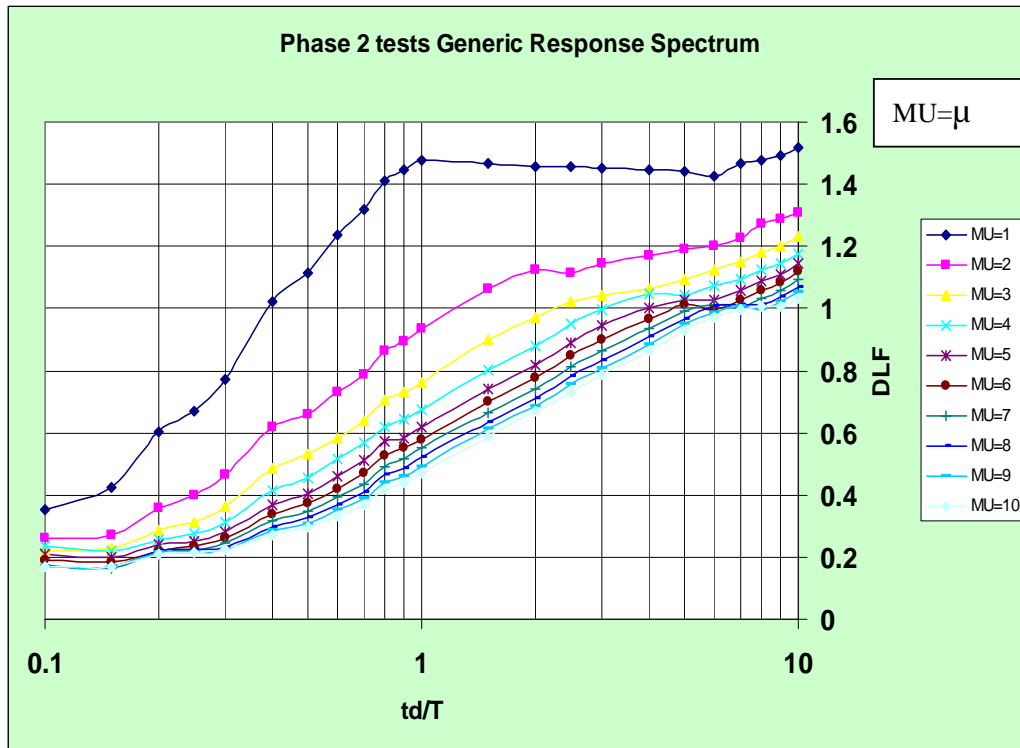


Figure XXX.8 Mean Response Spectrum for All Phase 2 Tests (DLF=R/Pe)

Figure XXX.9 below is a Response Spectrum chart obtained by averaging all response spectra for the FLACS analyses performed to simulate the Phase 2 full scale explosion experiments.

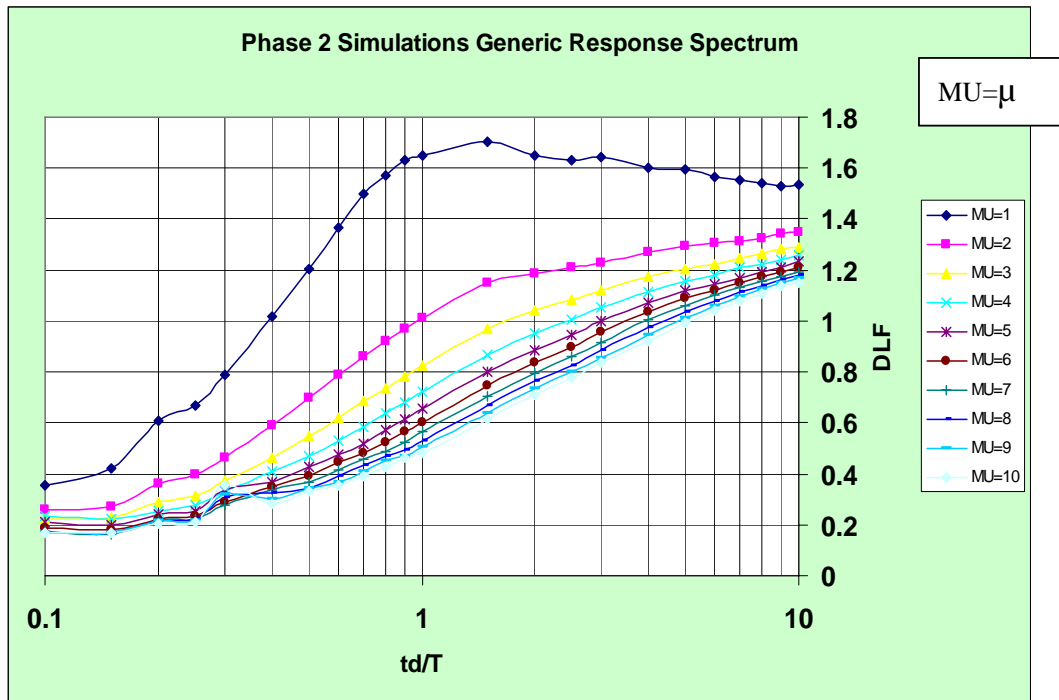


Figure XXX.9 Mean Response Spectrum for All Phase 2 Simulations (DLF=R/Pe)

The main difference between the experimental and simulated response spectra is the presence of high frequency loading components which are present in the experimental traces and which show up as spikes on the experimental traces. The simulations are not able to represent these high frequency components. These high frequency components tend to stimulate response at small natural periods corresponding to large values of td/T .

Conversely the test results do not exhibit the peak in the response spectra around resonance (between $td/T = 1$ and $td/T=2$). Use of simulation response spectra will give conservative results in this range.

The response spectra for higher ductility's ' μ ' have the resonance around $td/T = 1$ suppressed.

Response Spectra were also constructed for the Phase 3 test results and simulations.

The strength level blast

Two levels of explosion loading are recommended for explosion assessment [2] by analogy with earthquake assessment. They are the *ductility level blast* (DLB) and the *strength level blast* (SLB).

The *ductility level blast* is the design level overpressure used to represent the extreme design event referred to in NORSOK [7] as the Dimensioning explosion load.

The *strength level blast* represents a more frequent design event where it is required that the structure does not deform plastically and that the SCEs remain operational. This load case is recommended for the following reasons:-

- The SLB may detect additional weaknesses in the design not identified by the DLB (robustness check).
- The prediction of equipment and piping response in the elastic regime is much better understood than the conditions which give rise to rupture. The SLB enables these checks to be made at a lower load level often resulting in good performance at the higher level (strength in depth).
- The SLB is a low consequence event important for the establishment of operability.
- This load case offers a degree of asset protection.

The SLB has conventionally been derived as an event with about 10 times the probability of exceedance as the DLB. One criticism of the approach is that the factor of 10 is arbitrary.

The response spectra give a means of relating the equivalent static pressure allowing plastic deformation ($\mu > 1$) to that where elastic response is required (the $\mu = 1$ curve). The ratio of these two values at a given t_d/T suggests a means of relating the strength level blast effective pressure P_{es} to the ductility level blast effective pressure P_e .

This enables the SLB effective pressure to be defined from the DLB without recourse to consideration of return periods. For structures which may require elastic response, such as temporary refuge framing, the strength level blast for this element is by definition equal to the ductility level blast.

Further development of the Spectral Response method

The Response Spectra method may be extended to multi-degree of freedom structures by analogy with the related earthquake response spectrum methods.

The modal periods of a multi-degree of freedom structure and the modal loads (which give rise to the deflected shape corresponding to each mode) can be obtained. Modal responses may be superposed following the methods used in Earthquake response analysis.

If the probability of exceedance associated with a given set of pressure time histories is known, then the reliability (or probability of failure) associated with a given static resistance may be calculated. The Response Spectrum curve for a given ductility may be considered to be a failure surface. Points below the curve represent resistances which give higher peak response.

The current simulations have assumed elastic / perfectly plastic behaviour. For large deflections, tension and membrane effects will be important. Membrane effects and geometric stiffening effects may be incorporated into the method by the use of a modified resistance displacement formulation [8].

Multiple loadings (on an extended blast wall for example or for a number of design scenarios) may be superposed by considering the averaged response spectra. This will be a much more robust process than attempting to combine the traces directly.

Confirmation of the approach

Some variability between the Response Spectra between traces for a given test has been observed associated with:-

- Incompleteness of information
- Frequency components in the load trace (e.g. Biggs 'ripples')

These variations should be distinguished from legitimate variability between tests. Some selective averaging may be instructive. (low intensity traces not being considered).

The variability could be related to the physical test conditions. A parametric representation of the effective pressure P_e related to the test physical conditions would extend the applicability of the method.

There is still a large amount of data (experimental and simulated) available for further analysis arising from consideration of partial gas clouds and deluge, this should be processed and examined.

The relative invariance of response spectra for similar physical situations (e.g. the Phase 3 repeatability tests) indicates that comparison of these spectra would be a more robust method of comparison in the context of dynamic non-linear response.

The application of to actual existing designs could be used to assess the conservatism (or otherwise) of the conventional methods of load simplification/combination.

Nomenclature

T = Natural period – the time required for a freely vibrating structure to complete one cycle of motion. (s)

μ = Ductility – The ratio of peak deflection to the deflection at first effective yield (also appears in some figures as μ)

t_d = Load duration (s)

I^+ = Positive impulse of pressure trace up to the first intercept with the axis after the peak.

R = Resistance at effective yield (mbar)

P_e = Effective pressure in a pressure trace (mbar) ($=2I^+/t_d$)

P_{peak} = Peak pressure from pressure trace (mbar)

$P_{stat} = R$ = Equivalent static Design pressure

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