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Response Spectra for Explosion Loading and Response

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Abstract

Currently, explosion loads can only be specified realistically towards the end of detailed design. This has led to late design modifications and project delays. To date, little work has been done on using the available experimental data to generate better design guidance.

At an early project phase, there is a need for some quantitative guidance on the characteristic magnitudes of the explosion loads to be used in any given situation, ideally without recourse to detailed Computational Fluid Dynamics (CFD) simulation.

Previous work has been performed to produce ‘Nominal Overpressures’ as an early indication of the magnitude of the explosion hazard, but the variability of the loading and the dynamic characteristics of target structures makes the derivation and use of valid nominal overpressures difficult.

It has been observed that the Fourier transforms (or spectra) of explosion pressure traces have a very similar form for a given release/dispersion/ignition scenario during the development of the explosion and throughout the explosion region. This similarity of form has also been observed between different scenarios and between test results and CFD simulations

The work described in this paper is ongoing and aims to drive ‘envelope’ or generic response spectra which may be used for design and can be interpreted as representing equivalent static loads for a wide variety of explosion situations and target structures. This approach is similar to that already used in earthquake response analysis.

Background to the spectral response method

Summary of the approach. The response spectrum approach takes into account the variations in response of structural elements resulting from their differing natural periods and enables the reserves of strength released when elements are allowed to deform plastically to be taken into account.

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 [1].

Figure 1 at the end of this paper shows the application of blast response spectra in determining a static design pressure. The severity of the blast loading is determined from local conditions by the use of nominal overpressures, previous experience, risk classification, simulations or experiment. The structural element to be assessed may be a panel, a deck, module or a whole topside if they can be idealized as a one degree of system oscillator. This process will be familiar to designers who use the Biggs response method [2] and is in routine use.

The structural element is represented by its natural period and resistance at effective yield. A further important parameter is the allowable ductility of the element which is a measure of the amount of deformation an element can sustain before rupture or when its performance standards cease to be satisfied. This is usually expressed as a multiple of the peak elastic displacement. The allowance of local plastic deformation is an essential part of efficient blast resistant design.

The element natural period determines where we are on the horizontal axis (Figure 1) and the design pressure or required static resistance may be read off the relevant curve representing the allowable ductility.

It has been found that the response spectra for differing ductilities may be scaled using energy and impulse arguments to lie close to each other as shown in the Figure. The envelope of these scaled curves is indicated as the solid line and this is a generic representation of the dynamic and plastic characteristics of a wide range of structural elements.

Historical review. In the 1970's Newmark and others [4,5] examined a small number of earthquake records from the 1940's and developed response spectra for systems with a range of natural periods 'T' for a range of allowable ductilities 'μ'. They noticed that the response spectra derived from measured data bore a resemblance to the generic response curves shown in Figure 2.

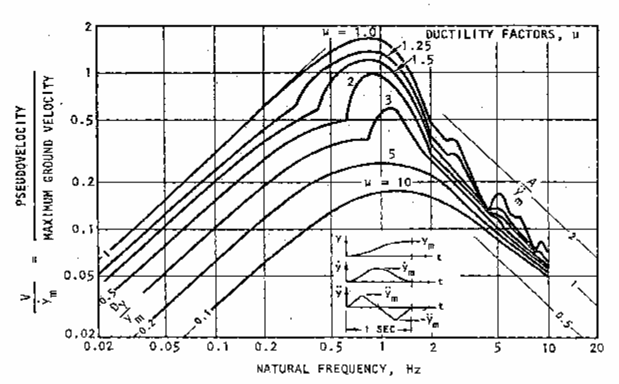

Figure 2 Deformation Spectra for undamped, Elastoplastic Systems Subjected to a half cycle velocity pulse [3]

The curves show the theoretical response to a half cycle velocity pulse of unit duration 'td' for systems with natural periods 'T' between 0.05 and 50 seconds or natural frequencies (1/T) between 0.02 and 20 Hz. Allowable ductilities between 1 and 10 are shown. In earthquake response velocities are plotted relative to the structure and not a fixed point on the ground hence the term 'pseudovelocity'.

The values on the displacement and acceleration axes are indicated on the left and right hand sides of the Figure. To view the curves as displacement curves tilt the figure 45° to the left. Most spectral response curves in this paper are presented in terms of displacement with a linear scale.

The curves in Figure 2 may be generalized by considering a load duration of td and plotting the dimensionless parameter td/T as the horizontal axis with the same numerical values as shown. These curves represent a generalization of conventional shock spectra [5] for elastic systems which are restricted to ductility 1.

The ability to replace 1/T by the more general td/T is a result of the fact that the frequency components of the loading (Fourier components) amplify, by resonance, the response of those systems whose natural periods match the frequency component considered

Figure 3 at the end of this paper illustrates the response spectrum method as it is applied in API for earthquake response calculations based on reference [6].

The structure to be analysed is idealised as a single degree of freedom system (SDOF) or as a series of single degree of freedom systems corresponding to each mode of response. The natural period and yield resistance 'Re' for each of these one degree of freedom systems is calculated from the effective mass, stiffness and static yield deflection.

Once the structure natural period and resistance has been determined the corresponding horizontal design acceleration may be read from the appropriate response spectrum curve.

As in explosion response, an allowable ductility may be associated with a particular structural type or configuration. A high allowable ductility will have the effect of reducing the effect of dynamic amplification through energy absorption and will result in reduced effective design accelerations and a reduced required yield resistance. Some early researchers have incorporated this effect into their design response spectra by multiplying the response spectra directly by the ductility 'μ'. A number of scaling schemes have been used to generalise earthquake response spectra to represent ductile response beyond yield and to make the spectra collapse down to a single curve [7]. This has the advantage for initial design that only elastic response analyses need be performed and a single generic curve can be made to represent response at differing ductilities.

Current practice in explosion assessment

The practice in the past two decades in assessing explosion loads can be summarized as follows:

Derivation of Loading. Specialized CFD gas explosion codes (e.g. FLACS) are often used, the other two methods are empirical and phenomenological models. These CFD codes give pressure-time histories for the loading on different parts of a structure on a platform. These codes require and accurate geometric representation of equipment, pipework, structure and deck arrangements and can predict overpressure loadings for a wide range of scenarios.

Loading idealization. Loads are then idealized to a triangle with only the positive phase included. Figure 4 [7] shows the conventional idealization of a pressure trace.

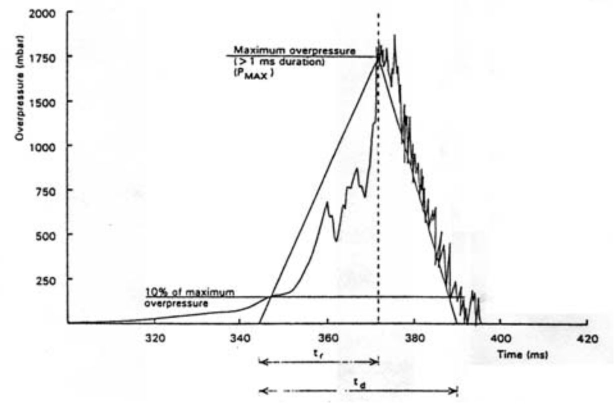

Figure 4 Idealized pressure trace for a hydrocarbon explosion [7]

In many instances, explosion loading is not adequately represented by the triangular simplification. It is preferable to use the original pressure traces from CFD or use a spectral based approach as described later.

Equivalent static loads. In early design stages an equivalent static load can be used to progress the primary structure design. A dynamic amplification factor (daf) must also be included and purely elastic response may also need to be assumed.

Another technique is to perform a simplified dynamic analysis and find an equivalent static load distribution which gives similar displacements to the peak dynamic response. This only applies for elastic response analysis but has the advantage that code, utilisation or unity checks maybe performed using conventional software. An increased utilisation, greater than one, may be accepted to include strain hardening and allowable plastic deformation.

Response assessment methods. The general philosophy is to start with the simplest methods (ensuring a conservative approach) and if failure is indicated proceed to more sophisticated methods of analysis.

The three main levels of analysis are:-

1. Screening analysis
2. Strength level analysis
3. Ductility level analysis

These are described in detail in References 12 and 11.

Component response - Biggs method [2]. Components may be analysed in isolation as long as the interaction with the surrounding structure through fixity and the applied loads are negligible or are represented in the component model.

The Biggs method requires two basic inputs, the resistance displacement curve and a loading time history. Design charts are available for the calculation of the peak response, x_{max}, given the load duration to natural period ratio td/T and the ratio of peak overpressure load to component ultimate plastic resistance. The method has traditionally been based on a triangular idealization of the pressure time history. The response spectra generated as part of this work have avoided the limitations of this assumption by using experimental or simulated time histories generated using the FLACS CFD code. The charts are based on a simplified bi-linear resistance behavior, which is inaccurate for fully or partially fixed members as well as for members where tension effects are significant.

The prediction of rupture using this method is unreliable as there is no detailed representation of the strain distribution within the structure.

Although some of the limitations seem severe, the technique has been successfully used in design situations, particularly where the resistance function has been accurately determined. If the resistance function is determined via a static non linear finite element analysis (NLFEA) the deflection time histories can compare well with an explicit dynamic NLFEA. This model may be unable to give accurate deflection values at high deflections due to the spread of plasticity which results in a change of the shape function used in formulating the spring mass idealization.

Limitations of the current approach. The current approach has a number of weaknesses. In early stages of design it can be difficult to provide a suitable estimate of the explosion loading since the most reliable means of doing so relies on an accurate understanding of the design that will not be available until it is nearly complete.

It is currently impossible to predict the high frequency content observed in measured pressure time histories. This has implications for both the structural response and again the inherent variability.

Current practice also often adopts an idealization of the pressure time history that is inappropriate

Explosion overpressure loads

A number of large scale tests were carried out at the Spadeadam test site in the UK between 1990 and 2002. In addition these explosion events were simulated using the CFD predictive code Flacs. Direct comparison of the pressure time histories and in particular the peak pressure values has been inconclusive.

The test results contained a large number of short duration spikes superimposed on a generally smooth curve as are demonstrated by the test pressure time history shown in the inset to Figure 5.

Whatever the cause of these spikes, investigations have shown that the influence of these short duration loads is insignificant for components with natural periods more than 0.02 seconds (natural frequency less than 50 Hz) which includes most components. These spikes which can take the observed peak overpressure Pmax beyond 12 bar make Pmax an unreliable measure of explosion severity. Pressure traces are often smoothed by time averaging over a period of 1.5 milliseconds effectively filtering out the high frequency components.

Because existing CFD explosion simulation codes do not generate these spikes as they cannot represent any of the processes thought to cause them.

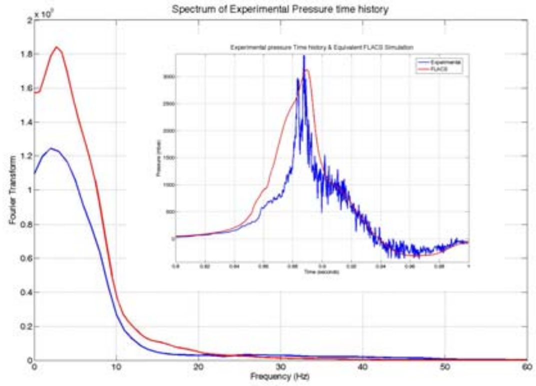

Figure 5 Comparison of experimental and simulated (FLACS) traces and their corresponding spectra

The red curves in Figure 5 are derived from simulations and the blue curves are experimental results.

Further work [8,9,10], has been performed to examine the experimental (Spadeadam) and CFD derived pressure traces in order to determine common characteristics which could be used to derive some ‘envelope’ curves to cover a variety of situations. The main conclusion of this work is that the impulse (integrated pressures over time) is a characteristic which is relatively invariant for any particular scenario.

Work [9,10], has also been undertaken to investigate the spectral characteristics of pressure traces, both experimental and simulated.

Figure 5 shows the spectra or frequency component representation of the pressure traces shown in the inset diagram. The red curve represents the FLACS simulation and the blue curve represents the corresponding experimental trace. The horizontal axis is frequency, the ordinate represents the energy present at each component frequency.

The two traces are of similar shape, with the experimental result having a larger contribution at higher frequencies. This shape is sustained for a large range of scenarios and for traces obtained at different times within any particular scenario. This similarity of shape has led us to the use of the response spectrum approach.

The response spectra of a range of structural systems with differing natural periods will reflect this distribution of load components, particularly if lightly damped elastic response is assumed.

Because of the way the pressure (input) spectra are constructed the value/component at zero frequency represented by the intercept of the spectrum with the vertical axis is equal to the square of the impulse in the original pressure trace.

A large number of pressure traces from experiment and their corresponding simulation traces have been examined as part of the present work. Figure 6 shows a number of response spectra from experimental (solid lines) and simulated (dashed lines) for ductilities of 1 to 5. For a target structure of natural frequency 100Hz (natural period 10 milliseconds) the required (static) resistance is 3.4 bar from the experimental trace and a required resistance of 4.8 bar is indicated by the simulation. In this case the simulation is conservative by a factor of 1.4. These values are fairly typical.

The peak pressure for the test shown was 7 bar with a simulated peak of about 6 bar.

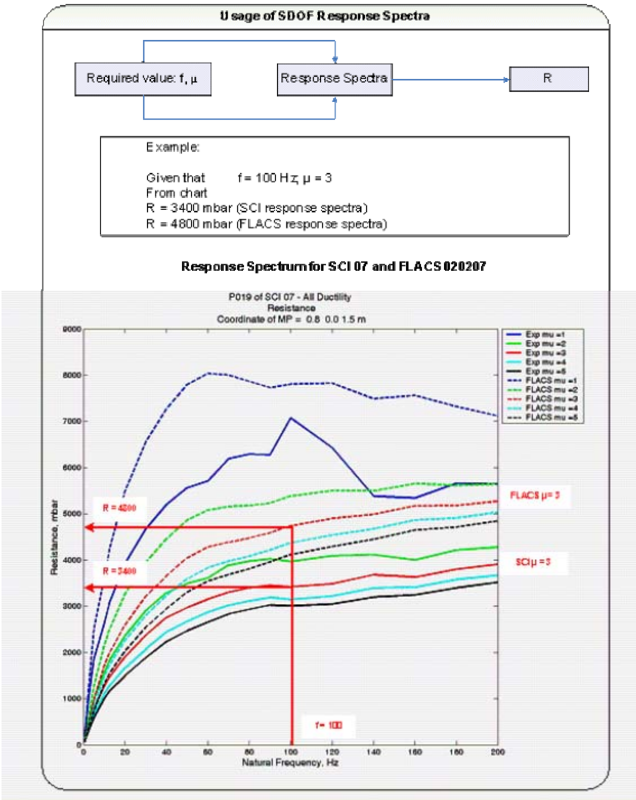

Figure 6 **Calculation of required (static) resistance simulated and test results.**

An explosion will produce a large range of pressures and impulses in a process area on a platform. Figure 7 gives an example of this for one of the tests at Spadeadam. Different part of the structure experienced different load for a given explosion scenario (e.g. ignition location). The design of the structure must be able to withstand loads from a large range of scenarios.

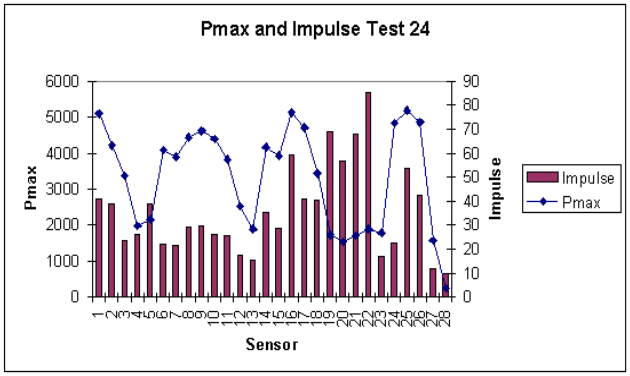

Figure 7 **Variation of Pmax and Impulse measured by sensors for Spadeadam Phase 2 Test 24**

In the assessment of the capacity of a structure to resist explosion loads, it is not sufficient to take only one scenario as defined by, release rate and location, gas cloud size, ignition position, ventilation conditions and ignition time. A number of scenarios with roughly equal probability of exceedance are chosen as representative of the explosion hazard. It is not acceptable to take benefit from low pressure regions for any particular scenario. In this situation the variability of the loading within the explosion region may be overcome by rational choice of design pressures time histories at different locations.

Representation of load intensity/severity. Impulse is an important measurement for explosion structural response and is an averaged measure as it includes all data in the pressure-time history. There is also a more consistent correlation between impulses for actual test results and CFD simulations.

Measures of Duration. Measures of load duration 'td' have been found useful in scaling the horizontal axis of the response spectra for earthquakes and Biggs response curves.

Figure 5 indicates the difficulties in attaching a meaningful value to this measure for experimental traces but a number of options are available and are under investigation.

a) The triangular idealization approach: In this case td may be defined in terms of Pmax and the impulse of the positive phase of the trace, by:-

$$t_d = 2/\mathrm{Pmax} \times \mathrm{Impulse}$$

b) Root mean square pressure of the Triangular idealization approach: 'Prms' in lieu of the Pmax value.

$$t_d^{\;2} = \text{Impulse of squared pressure} / (\mathrm{Prms})^2$$

c) A more rigorous duration measure may be related to the spectral peak and the median frequency which has equal energies at lower and higher frequencies. The corresponding measures for wave spectra are the zero crossing period and mean period, both of which may be calculated from moments of the spectrum or integrals across the frequency range of the spectrum multiplied by powers of the frequency.

Once an effective duration has been established response spectra may be plotted in terms of td/T as has been the case for the Biggs and earthquake response methods. Integrals of response spectra for use in response scaling may then be evaluated up to the appropriate natural frequency for the pressure trace considered in a consistent way.

Explosion response

Required static resistance Curves. Explosion response has conventionally been represented by the Biggs curves [2], where response curves have been constructed using an idealized triangular load time history similar to that shown in Figure 4. The curves represent the variation of peak response with load duration/target natural period td/T. The peak response curves are constructed for each selected value of the ratio of static elastic resistance/peak load, Re/Pmax.

The response spectra generated in the present work use the actual pressure time histories. The curves are constructed by considering the allowable ductility (from 1 to 5) and then plotting the Re required to limit the peak displacement to this value of ductility. The variation of this resistance with target natural period then gives rise to curves similar to those shown in Figure 8. This is the same presentation of results as that used in earthquake response as illustrated in Figure 2. The required static resistance may then be re-interpreted as an equivalent static load at each structural natural period.

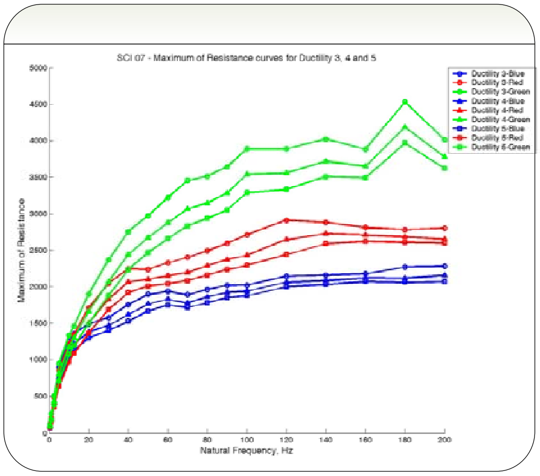

Figure 8 Experimental response spectra - Spadeadam Phase 2 test 7

Figure 8 shows the variation of required static resistance with target natural frequency 1/T for test 7 of Phase 2 of the Spadeadam tests. The response spectrum curves are grouped by distance from the ignition source. The blue, lower group are for pressure traces less than 8m from the ignition source, the red, middle group are between 8 and 16m from the source and the green, upper group represent response to pressure traces more than 16m from the ignition source.

Structures with high natural frequency relative to the reciprocal of the load duration or with natural periods less than 1/3 of td are able to respond to the load time history point by point and are referred to as responding in a pseudo-static way in the energy regime of response. This corresponds to the high frequency, right hand, end of the figure.

Structures with low natural frequency or with natural periods more than about 3 times the load duration respond impulsively to the total impulse in the load. This response is virtually independent of the shape of the load time history and is referred to as responding impulsively. These are represented by points to the left of the figure. Generally impulsive response is much smaller than that indicated by the peak load as the structure does not have time to respond. This is indicated by the much reduced response or required resistance at this end of the response spectrum.

Allowable ductilities. The allowable ductility is assessed for the structure by consideration of the connection detailing and framing. The allowable ductility may also be derived from a known reserve strength ratio in combination with the performance standards appropriate for the situation. For example, small allowable displacements (μ ~1) for the Temporary Refuge and supports of critical systems, and large allowable deformation (μ ~5) for equipment and piping supports, cladding and blast walls.

Response scaling – impulsive and energy bounds. It has been found to be possible to scale the response spectra for selected traces to bring them together to lie closely on one representative curve which then allows an envelope spectrum to be constructed to represent all allowable ductilities with correct scaling of the resistance axis.

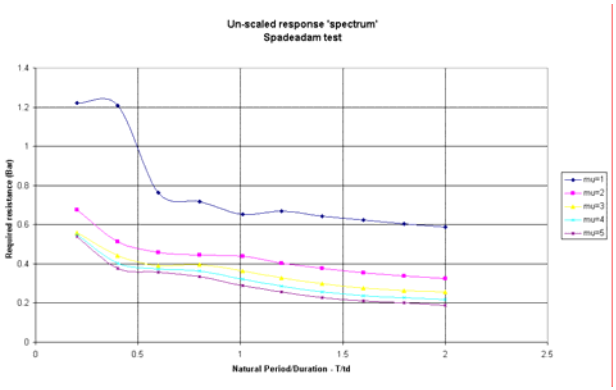

Figure 9 Displacement response spectra for a typical experimental trace variation with T/td

As described above the extreme ends on the spectra represent regimes where approximations may be made to derive the response.

In Figure 9 the left hand side (T/td<0.3) represents the regime where the natural period is sufficiently small for pseudo-static response to be considered. The energy at peak deflection is then equal to the work done by the external force and it may then be shown [13] that:-

$$R1/R\mu = \sqrt{(2\mu - 1)} \qquad (T \ll td)$$

Where R1 is the required elastic resistance and Rμ is the required resistance at ductility μ. This may be interpreted as an approximate relationship between the elastic response spectrum and the response spectrum for an allowable ductility of μ at small ratios of T/td.

In Figure 9 the right hand side (T/td>3) represents the regime where the natural period is sufficiently large for impulsive response to be considered. Here it may be assumed that at zero deflection all the energy is in the form of kinetic energy of the target which then is absorbed as strain energy at maximum deflection. In this case:-

$$R1/R\mu = \mu \qquad (T \gg td)$$

In the intermediate region between these two limits true dynamic response occurs. The two formulae above have been combined by Newmark to give an approximate general formula over the natural period range as:-

$$\frac{P_{\max}}{R_\mu} = \frac{T}{\pi t_d} \cdot \sqrt{2\mu - 1} + \frac{1 - 1/(2\mu)}{1 + 2T/(\pi t_d)}$$

This formula enables R1 and Rμ to be related through Pmax which is the same in both cases. The formula is stated to be accurate to within 10%.

When the ratio of R1 and Rμ is applied to the curves in figure 9, the resulting spectra are as shown in Figure 10. The curves now approach each other and an envelope curve may be easily constructed. The elastic curve at μ = 1 shows some departure from the others at low natural periods as it follows the loading more closely. This is because the response occurs without plastic deformation which itself is an energy absorbing mechanism. The introduction of a small amount of damping into the system has the effect of smoothing all the response spectra.

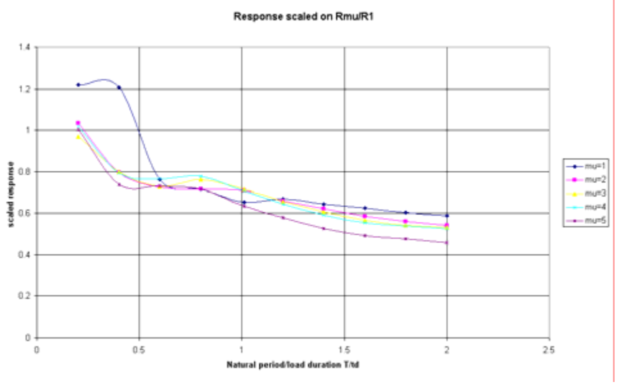

Figure 10 Scaled Displacement response spectra

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Nomenclature

T = Natural period – the time required for a freely vibrating structure to complete one cycle of motion. (secs)
μ = Ductility – The ratio of peak deflection to the deflection at first effective yield.
td = Load duration (secs)
Re = Resistance at effective yield (bar) = R1
R1 = Required resistance at yield/ equivalent static load at ductility 1 (bar)
Rμ= Required resistance at ductility μ / equivalent static load at ductility μ.
Xe = Static yield deflection, deflection at first effective yield.
Pmax = Peak pressure in a pressure trace (bar or millibar)
P_{static} = equivalent static load (using dynamic amplification factor)
Prms = Root mean square value of a pressure trace P

Conclusions

Experimental and simulated explosion pressure traces have been processed and compared and their underlying structure examined.

The common spectral form for experimental and simulated results has been identified.

The response spectrum approach has been described, which differs from the 'nominal overpressure' approach in that the dynamic characteristics and allowable deformations of the target structure are represented

The design response spectra give the required static resistance and the load level to be used for simplified explosion resistant design and assessment.

The factors to be considered in scaling response spectra to give more generally applicable response curves have been examined. These include:-

- Load scaling by Impulse, modulus and squared impulse.
- The influence of the spectral shape of the input loading
- Response scaling by definition of an effective load duration
- Response scaling between allowable ductility values

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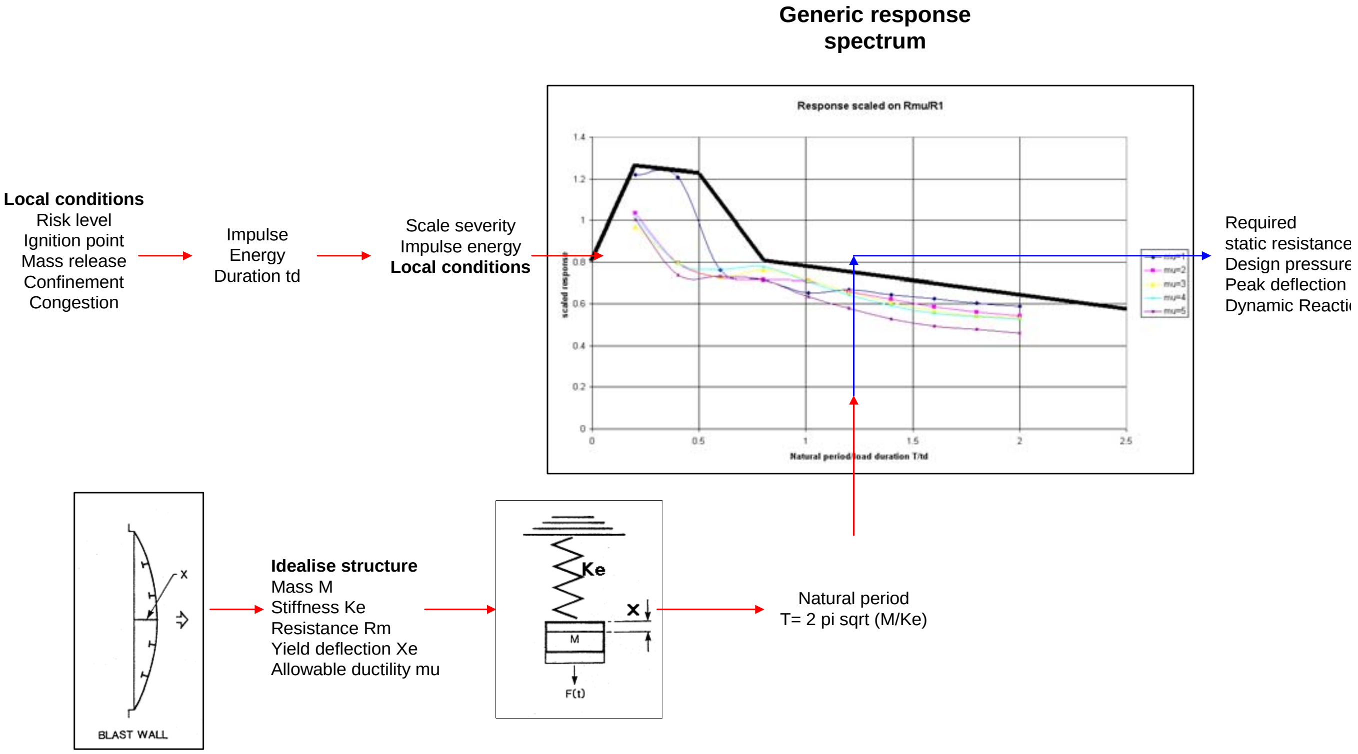

Figure 1 The Use of Explosion Response Spectra to Determine Equivalent Static Loads.

Figure 3 (Below) The Response Spectrum method as applied in Earthquake Response