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Clearing of blast waves on finite-sized targets – an overlooked approach

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Abstract

The total impulse imparted to a target by an impinging blast wave is a key loading parameter for the design of blast-resistant structures and façades. Simple, semi-empirical approaches for the prediction of blast impulse on a structure are well established and are accurate in cases where the lateral dimensions of the structure are sufficiently large. However, if the lateral dimensions of the target are relatively small in comparison to the "length" of the incoming blast wave, air flow around the edges of the structure will lead to the propagation of rarefaction or "clearing" waves across the face of the target, resulting in a premature reduction of load and hence, a reduction in the total impulse imparted to the structure. This effect is well-known; semi-empirical models for the prediction of clearing exist, but several recent numerical and experimental studies have cast doubt on their accuracy and physical basis. In fact, this issue was addressed over half a century ago in a little known technical report at the Sandia Laboratory, USA.

This paper presents the basis of this overlooked method along with predictions of the clearing effect. These predictions, which are very simple to incorporate in predictions of blast loading, have been carefully validated by the current authors, by experimental testing and numerical modelling. The paper presents a discussion of the limits of the method, concluding that it is accurate for relatively long stand-off blast loading events, and giving some indication of improvements that are necessary if the method is to be applicable to shorter stand-off cases.

Introduction

It is self-evident that in order to be able to analyse and design protective structures subjected to blast loading, we must be able to quantify with some degree of confidence the key parameters of the blast load. In addition to knowing the rate and magnitude of energy release during a detonation, we must also be able to determine how the subsequent blast wave will propagate through the medium between the detonation and the target, and how it will then interact with the target Historically, four methods have been employed to produce these propagation and loading data.

1) Closed form mathematical analysis of shock wave propagation/interaction.

2) Experimental test data

3) Numerical analysis of the relevant differential equations governing shock propagation and target interaction

4) Empirical or quasi-empirical prediction methods.

The first of these, whilst giving useful insights is practically suitable only for the very simplest geometrical cases. Experimental work, if well conducted is perhaps the most accurate approach, but also the most expensive and time consuming. Numerical analysis methods have made a transition from specialist research tools to use in practical design over the last two decades, but their use still requires considerable experience and expertise and to accurately model blast waves often requires large computational resources. Consequently, for many years quick, approximate methods have been used by drawing on a database of existing empirical results from numerous blast load experiments and using scaling laws to predict loading parameters for particular combinations of explosive type, explosive mass, placement and distance from target. These methods are necessarily approximate and can apply only to relatively simple geometrical scenarios, but they do have the benefit of allowing blast load parameters to be determined with negligible computational effort.

Such semi-empirical prediction approaches can be found in several publications, [e.g. 1,2] and an example of such predictions is shown in Figure 1, where the relationships between peak reflected pressure (p_r), positive duration (t_d) and specific impulse (i_r) generated when a blast wave from a the detonation of a spherical charge of TNT is detonated in air at sea-level and propagates to a target without encountering other obstacles. It is important to note that the magnitude of the *reflected* pressure and impulse, generated when a blast wave impinges onto a nominally rigid target are typically considerably higher than the *side-on* or *incident* values that would be experienced by a target face parallel to the direction of propagation of the blast wave. This is due to the shock itself being reflected by the target, and a proportion of the kinetic energy of the displaced air particles being converted to pressure energy as they impact upon the target.

Figure 1 also introduces the concept of *scaled distance*, scaled distance (Z),

$$Z = S / W^{\frac{1}{3}} \qquad (1)$$

where S =distance from detonation point to a target and W = the mass of the explosive charge.

Scaling of blast wave parameters is based on the premise that, for geometrically similar detonation events at different length scales, the peak pressure and *scaled* specific impulse and duration (actual specific impulse and duration divided by the cube root of the charge mass) will be constant at the constant scaled distance. Since the energetic output of explosives vary with their chemical composition, the mass of the explosive charge used in determining the scaled distance in (1) is given in terms of “equivalent mass” of a standard explosive, typically TNT, by multiplying the actual mass by an empirically derived equivalence factor. Thus, data from a large number of disparate experimental trials can be combined into simple load prediction relations. The US Army computer code ConWep provides a quick-running computational prediction of blast load parameters based on just such relations. For simple geometrical scenarios, with sufficiently large scaled distance, ConWep’s predictions correlate well with carefully controlled experimental data. For example, Figure 2 shows ConWep predictions for the reflected pressure-time history data from a blast wave generated by the detonation of a 250g C4 hemispherical ground burst, impinging normally on a target wall at a distance of 4m, together with the pressure data from an experimental test conducted at University of Sheffield’s (UoS) blast research laboratory. The graph also shows the time of arrival at the target (t_a) and the negative phase following the main positive blast pulse, which is due to a partial vacuum due to an overexpansion of the air medium as the blast wave propagates through it.

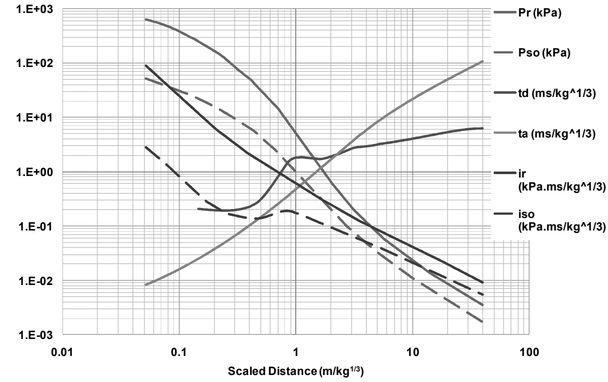

Figure 1. Reflected blast wave parameters for a free-field air explosion using a spherical TNT explosive charge.

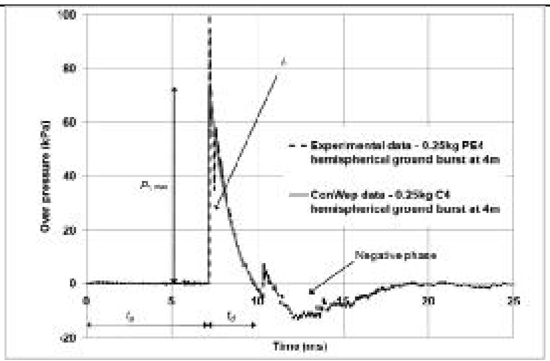

Figure 2. Comparison of ConWep prediction and experimental trial data for reflected pressure from 250g C4 hemispherical groundburst charge at 4m

The Clearing Effect

The data shown in Figure 2 applies only if the target is sufficiently large for edge effects to be negligible. If a plane blast wave front impinges on a rigid target with finite lateral dimensions, immediately adjacent to the free edges of the target, the pressure will rise to the reflected peak overpressure value, but then reduce as flow conditions are established around the free edge. A pressure differential will therefore be set up along the loaded face, resulting in a rarefaction wave propagating inwards along the target face. This will result in what is known as the “relief” or “clearing” effect, whereby the pressure at a given point on the target face will prematurely reduce to below that suggested by, for example, Figure 2. The time at which the clearing wave arrives at a given point depends on the distance of that point from the nearest free edge and the speed of propagation of the rarefaction wave, whilst the magnitude of the premature pressure drop is a function of the magnitude of the pressure difference in the cleared and un-cleared regions of the loaded face.

This effect has been recognised for many years, and several empirically based approaches have been proposed to account for it. The most widely used approach [2-4] is shown schematically in Figure 3. It is assumed that the pressure on the target face decays from the reflected value to a

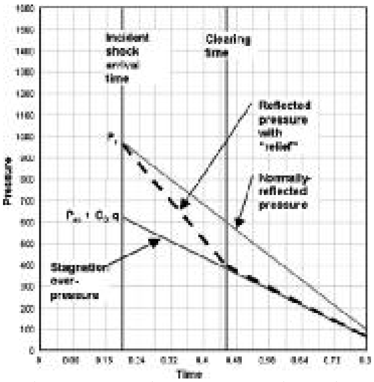

Figure 3. The conventional approach to clearing [5].

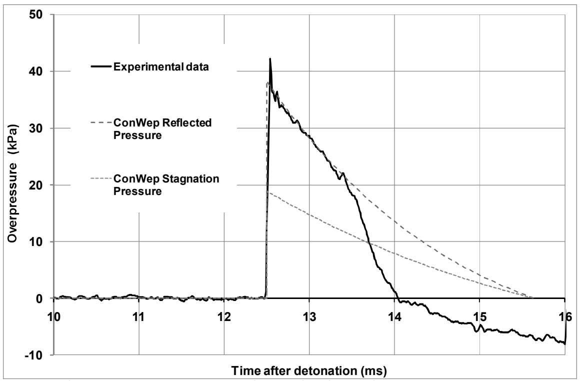

Figure 4. Example of clearing. 250g C4 hemispherical ground-burst explosive charge 6m from 710mm wide by 675mm high target

"stagnation" value (the sum of the side-on pressure plus a dynamic pressure from the air flow around the cleared target) over some characteristic "clearing time". Various formulae have been proposed for calculating the clearing time, but, as noted recently, both the proposed clearing model and the clearing time calculations have little apparent physical validity [5]. This is demonstrated in Figure 4, which shows an experimental pressure-time trace obtained at the UoS laboratory, from the centre of a small vertical target subjected to a loading from the detonation of a hemispherical 250g charge of C4 explosive set on the normal from the centre of the target base at a distance of 6m from the target, together with ConWep predictions for the reflected and stagnation pressures. It is clear from this data that the pressure experienced at the centre of the target in fact follows the reflected pressure curve initially, before falling rapidly to *below* the stagnation pressure as the clearing rarefaction wave arrives from the free edges. In fact the experimental pressure become net negative shortly after onset of clearing, indicating that the clearing effect significantly shortens the duration of the positive phase of the loading.

A rediscovered approach to clearing – The Hudson approach

The questionable validity of the existing approaches to clearing has resulted in a number of other studies of the clearing problem over recent years, aimed at developing more sophisticated clearing prediction algorithms from experimental data [5] or numerical analysis [6]. In fact, researchers at UoS have a recently re-discovered a more physically rational approach to this problem, which was developed in the 1950s and subsequently classified for the next half-century, leading to it apparently being entirely overlooked by the blast loading community. The work, conducted by Hudson at Sandia National Laboratory [7] was based on an acoustic analysis of the propagation of the rarefaction wave from the free edge(s) of a target. A number of simplifying assumptions were made in order to produce soluble equations. These assumptions included:

1. The incoming blast wave front is plane and parallel to the target surface. (This implicitly requires the target dimensions to be small relative to the distance to the detonation point.)
2. The depth of the target is sufficiently large for effects due to diffraction/rarefaction of the wave at the rear face to be ignored when considering the front loaded face.
3. The rarefaction clearing wave propagates into stagnant air across the target face. (That is, no flow conditions exist in parallel to the target face in the compressed air into which the clearing wave travels. This means that the analysis is not strictly correct if two or more rarefaction waves meet and cross over.)
4. The propagation velocity of the rarefaction wave is equal to the ambient sonic speed in uncompressed air at sea level. (This limits the method to ranges over which the reflected pressure is relatively low – Hudson himself considered that this assumption was reasonable for magnitudes of peak incident pressure <~300kPa, which equates to a scaled distance of approx. 2.0m/(kg$_{\text{TNT}}$)$^{1/3}$.

To facilitate the analysis, Hudson used two non-dimensional parameters. The first factor, η, was the distance which the clearing wave must travel from a free edge to a given point on the target face divided by the physical "length" of the incoming blast load in the absence of clearing. Hudson's showed how, given assumption 4 above, this length could be taken as the product positive duration of the incoming blast load t_d, and the ambient sonic velocity in air a_0. It follows that η=0 refers to a point on the free edge, where clearing will commence immediately, whilst η>1 is a region sufficiently distant from a free edge that the reflected pressure will decay to zero before the clearing wave arrives, and the entire positive reflected pressure duration is experienced. The region $0>\eta>1$ will experience some duration of reflected pressure before this reduces following the arrival of the clearing wave. The second factor was essentially $(t-t_a)/t_d$, the time after arrival of the blast wave normalised against the positive duration (although Hudson actually presents this in terms of distance travelled by a wave in time $(t-t_a)$ non-dimensional against the length of the incoming blast wave).

Hudson derived the magnitude of the clearing wave was then as a function of these two parameters; since the graph in [7] presenting these data are not of high quality, examples of the clearing function vs time (normalised against the peak incident pressure) have been extracted and shown in Figure 5 for various values of η. With these data, the cleared pressure-time history could then be found by superimposing the ideal blast loading pulse ignoring clearing and the negative clearing effect. Figure 6 shows an example of the very good correlation between the cleared pressure prediction derived this way and the experimental data from Figure 4. Figure 7 is an alternative way of presenting these data, showing how the Hudson method gives a very good prediction of the temporal development of the specific impulse seen in the experimental test.

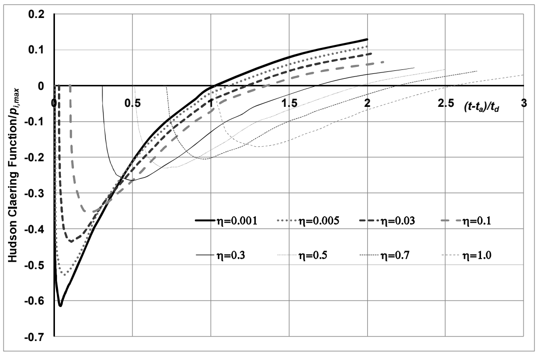

Figure 5. Hudson Clearing function

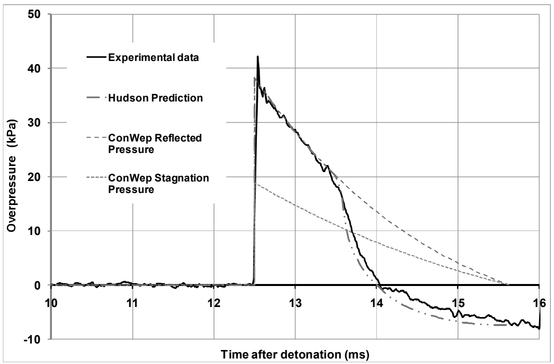

Figure 6. Data from Figure 4 with Hudson clearing prediction added

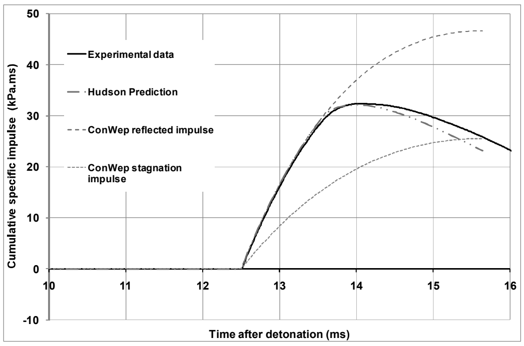

Figure 7. Cumulative impulse vs time data from Figure 6

Discussion and conclusions

The experimental and Hudson prediction data presented above show clearly how the clearing effect can significantly reduce both the total impulse experienced by the target, and the positive duration of the load. Structural response under blast loading is often highly sensitive to these parameters. The Hudson approach appears to offer a valuable and efficient way in which predictions of the cleared pressures and impulses at different points on a target face could be calculated by designers and used as loading functions for quick initial parametric studies on likely blast damage.

Additional tests conducted at UoS indicate that the Hudson method gives good predictions for ranges 4-10m for the 250g C4 charge, which, with an TNT equivalence factor for C4 of 1.2 equates to scaled distances of 6-15m/$kg_{TNT}^{1/3}$, with the scaled target face dimensions being approximately 1m/ $kg_{TNT}^{1/3}$. This means that the Hudson method might be applicable in the case of, say, a 300kg TNT explosion 40-100m from a 7m x 7m target face. At this range, structural damage would be unlikely, but damage to glazing and light cladding could be significant.

At distances below 4m, in our work, the Hudson prediction appears to become less accurate, presumably due to the decreasing validity of assumptions on the plane blast wave front and relatively low reflected pressure magnitude. It should be remembered that Hudson made these assumptions purely to facilitate his closed-form mathematical analysis almost 60 years ago. It is possible that his analysis framework could be used with numerical solution strategies to produce accurate predictions where these assumptions do not apply. Work is ongoing at UoS on this topic.

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