Full Paper

Propellants, Explosives, Pyrotechnics

DOI: 10.1002/prep.201300094

The Effect of the Relief Wave on the Uniformity of an Air Blast Load

Abolfazl Shoja,[a] Mohamad Ali Adabi,*[a] Masoud Ahmadnia,[a] and Jamal Zamani[b]

Abstract: In most blast loading structure analyses, it is assumed that the load acts uniformly on a target area. For the rationable design, it is useful to have a quantitative criterion to determine at which maximum distance the standoff can be placed to assume a uniform pressure distribution. Surprisingly, no standard criterion was found in the literature and the effect of blast wave clearing was not considered as well. In this paper, pressure histories applied on structures are calculated considering the non-uniform loading characteristic as well as pressure relief from the edges. Additionally, the effects of various parameters on uniformity of impulse distribution are investigated. The results have shown that the effect of pressure relief on impulse uniformity is very important, especially when the blast wave is attenuated. This phenomenon leads an optimum distance at which impulse distribution is the most uniform.

Keywords: Airblast · Impulse uniformity · Blast wave · Reflected pressure · Pressure relief

1 Introduction

Blast loading structure analyses require well understanding of the applied pressure, the non-uniform distribution of which complicates the analyses. Therefore, most researchers have attempted to investigate situations, in which a uniform load can be assumed for the whole surface area of the plate. This assumption is based on the fact that blast wave acts like a nearly planar wave at far distances. However, no standard criterion was found to determine how far the distance of the explosion away from the target should be to produce a planar blast wave. Wei and Dharani [1] assumed a uniform blast wave at 14 m standoff distance with a charge weight equivalent to 4.54 kg TNT and 1963 × 965 mm^2 structure dimensions. Veldman et al. [2] verified such a wave in their experiments and measured the arrival times at different points at each test plate. Their measurements indicated when time arrivals are considered within 5 % deviation, the blast loading has nearly uniform distribution. Meanwhile, according to TM 5–1300 [3], a uniform loading can be assumed when the target is completely within the Mach stem of the blast wave. Furthermore, the U.S. Army Corps of Engineers [4] suggested that a uniform load is adequate when the scaled distance (Z) > 1.2–2. Rickman and Murrell [5] estimated that a planar wave is produced for $Z = 1.8$.

It has been recognized that reflected pressure time history can be strongly influenced by the pressure relief phenomenon, yet, its effect on impulse uniformity is not investigated. When the front face of a rigid, rectangular structure is impacted by an airblast wave, a reflected wave is immediately formed and greatly increases the pressure loading on the surface. This reflected pressure is substantially greater than the airblast overpressure in the immediate region. Thus, as the reflected wave reaches a free edge of the front face (where overpressure conditions exist), a flow of air commences from the higher to the lower pressure region. This flow proceeds as a rarefaction (relief) wave emanating from the free edges of the front face (top and sides) and progresses inward toward the center. As the relief wave arrives at a point on the front face, it begins to decrease or "relieve" the reflected pressure.

There are a number of approaches to predict the pressure-time history. The first was described by Glasstone and Dolan [6], which was later followed by various studies [3, 7–11]. Based on their point of view, shape and magnitude of the resultant waveform are achieved when the reflected pressure is allowed to decay linearly from peak pressure to the predicted stagnation pressure during "clearing time", t_c, after initial peak. The clearing time is defined as the time required for relief to be fully achieved (after incident shock arrival). Various equations are utilized to predict clearing time but there is considerable dispute regarding the time during which clearing or pressure relief has been fully achieved. This method is accompanied with three inevitable

[a] A. Shoja, M. A. Adabi, M. Ahmadnia
Manufacturing Faculty
Khaje Nasir Toosi University of Technology
Tehran, Iran
*e-mail: Ma.adabi@yahoo.com

[b] J. Zamani
Faculty of Mechanical Engineering
Khaje Nasir Toosi University of Technology
PO BOX 19395/1999, Tehran, Iran

© 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

errors: (i) considering blast wave as planar, (ii) reflected pressure waveform approximated by linear rather than exponential decay from the peak, and (iii) application of the relief wave at the beginning of incident shock arrival [5].

Hudson [12] introduced an acoustic pulse method, validated by some experiments, to predict the clearing effects [13]. Aside from complexities, there are some restrictions in its applications because of simplifying assumptions e.g. planar and weak blast wave impinging normally onto a flat target of finite dimensions.

Rickman and Murrell [5] developed an improved empirical methodology to predict the effect of pressure relief that showed a better agreement with experimental results. By some experiments, they estimated relief wave as an exponential function with coefficients varying with standoff distance.

In this paper, pressure profile applied to the plate from spherical charges was calculated considering two points: (i) spherical propagation for blast wave, and (ii) relief wave using Rickman's methodology. Afterwards, the effects of charge weight, standoff distance, and plate dimensions on impulse uniformity were analyzed.

2 Calculations for Impulse Applied on the Plate

For a blast (detonation) loading, chemical investigations and experimental data [4] show that a good representative simplified model is an exponential time history. One of the most frequently used blast models is exponential decay with an instantaneous peak pressure obtained from the modified Friedlander Equation (Equation (1)):

$$P(t)=\begin{cases}0, & t<t_a \\ P_s\left(1-\dfrac{t-t_a}{T_d}\right).\exp\left[-\alpha\left(\dfrac{t-t_a}{T_d}\right)\right] & t_a \le t \le t_a+T_d \\ 0, & t_a+T_d \le t\end{cases} \qquad (1)$$

where t_a is the arrival time, T_d the positive duration time, and α the exponential decay constant.

2.1 Spherical Effect

In most of blast loading analyses, for simplicity, the wave is considered as planar but this assumption sometimes leads to considerable errors. The reflected pressure tends to be decreased from center to edge of the plate because distance from charge (R_0) and also incident angle (θ_I) increase (Figure 1) The net pressure at each point on the target surface is determined directly from Equation (2) [4,14]:

$$P_{net}(Z,\theta_I) = P_r(Z)\cos^2(\theta_I) + KP_s(Z)\,[1-\cos(\theta_I)]^2 \qquad (2)$$

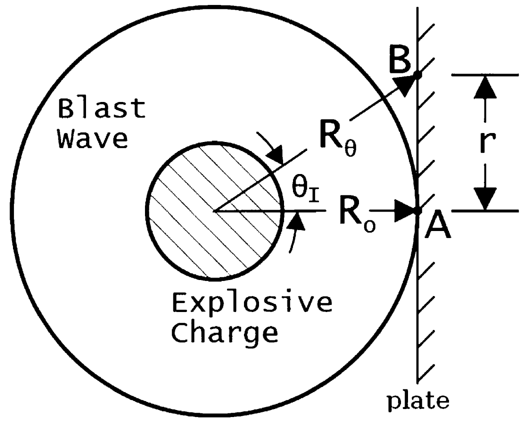

Figure 1. Geometry of an ideal blast wave impacting a flat surface.

where Z is the scaled distance, P_r is the peak of normal reflected pressure, P_s is the peak overpressure, and K is the weight factor. The net impulse for an oblique reflection can also be calculated from Equation (3) [4,14]:

$$i_{net}(Z,\theta_I) = i_r(Z)\cos^2(\theta_I) + Ki_s(Z)\,[1-\cos(\theta_I)]^2 \qquad (3)$$

where i_r is the normal reflected impulse and i_s is the side-on impulse. Therefore, considering Equation (2) and Equation (3), it is possible to obtain the net peak of reflected pressure and impulse. Using Equation (4), the net decay constant can be achieved numerically at each point in the plate from Equation (4) [9]:

$$\frac{P_{net}T_{net}(\alpha_{net}-1+e^{-\alpha_{net}})}{\alpha_{net}^2} - i_{net} = 0 \qquad (4)$$

2.2 Relief Wave

Theoretically, the reflected pressure is limited to stagnation pressure, but Rickman and Murrell [5] experimentally showed that this model tends to be rather inaccurate because the exact manner, in which the relief wave is manifested, is not accurately defined. They realized that the relief functions show similar patterns with the exponential decay and appear to be nearly identical for all structure sizes. They suggested Equation (5):

$$lnP = \mathrm{A} + \mathrm{B}\,e^{-t} \qquad (5)$$

where P is the pressure [kPa], t is the time [ms], and A and B are coefficients that vary with standoff distance (Figure 2). It is possible to predict the arrival of the relief wave from Equation (6):

$$t_r = t_g + \Delta t + S/U \qquad (6)$$

© 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

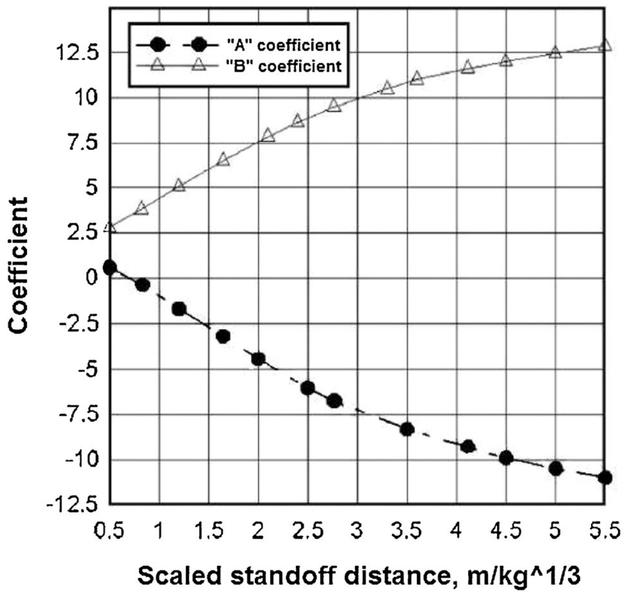

Figure 2. A and B coefficients vs. scaled standoff distance [5].

where t_r is the time of arrival of the relief wave, t_g is the time of arrival of the initial shock at the gage, Δt is the time difference between shock arrival at the target point and shock arrival at the closest structure edge, S is the distance from the measurement point to the structure edge, and U is the calculated relief wave velocity (Figure 3).

2.3 Verifications

The positive phase airblast loading parameters, P_r, P_s, T_d, t_a, i_r, and i_s, can be obtained from experimental data [9]. Using Equation (2) and (3), P_{net} and i_{net} are achieved and

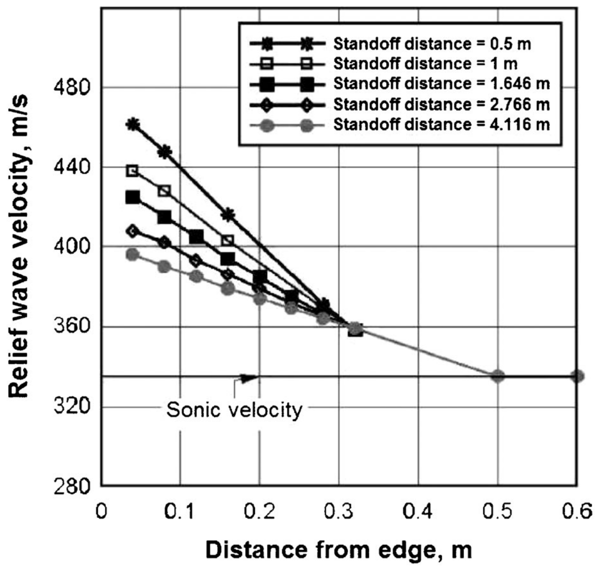

Figure 3. Average relief wave velocities for various standoff distances vs. distance from structure edge [5].

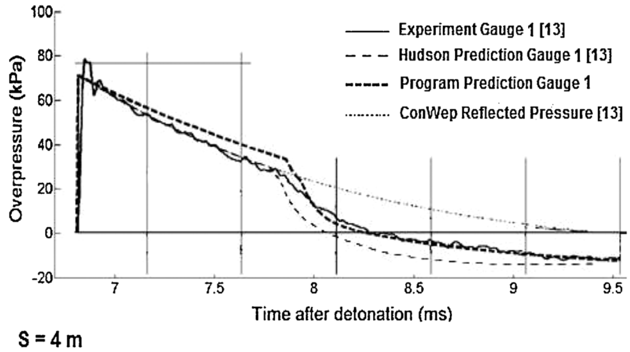

Figure 4. Pressure-time history for G1 at 4 m distance.

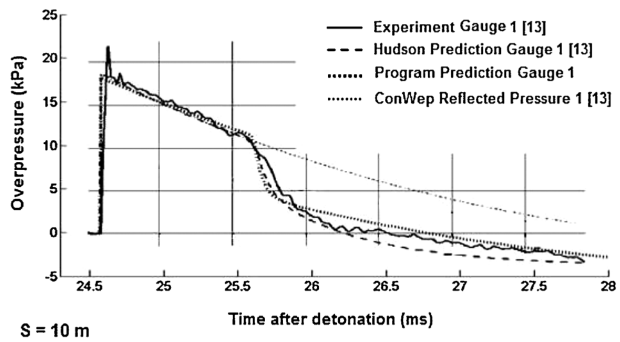

Figure 5. Pressure-time history for G1 at 10 m distance.

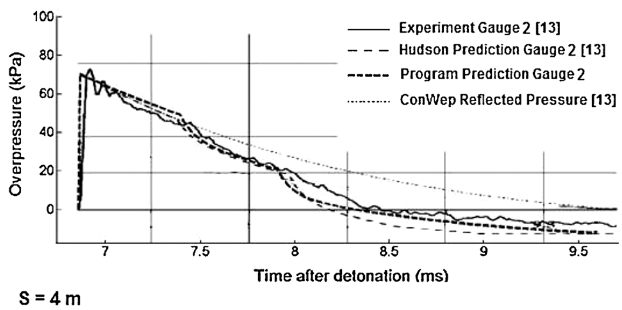

Figure 6. Pressure-time history for G2 at 4 m distance.

substituting their values beside T_d into Equation (4), decay constant is found by numerical methods. Having substituted all calculated parameters into Equation (1), the reflected pressure-time history will be obtained. Then, relief wave is modeled and added to Equation (1). Finally, the last pressure-time history is integrated to calculate the impulse for any point in the plate. At this point, a code was prepared using MATLAB to facilitate calculations.

Figure 4, Figure 5, Figure 6, and Figure 7 compare the experimental pressure profiles recorded in Ref. [13] with the results obtained by MATLAB and Hudson's suggestion. A number of simple explosive tests were conducted, each of which used 250 g C4 hemispherical explosive charges. The target was a large reinforced concrete block, located on

 © 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

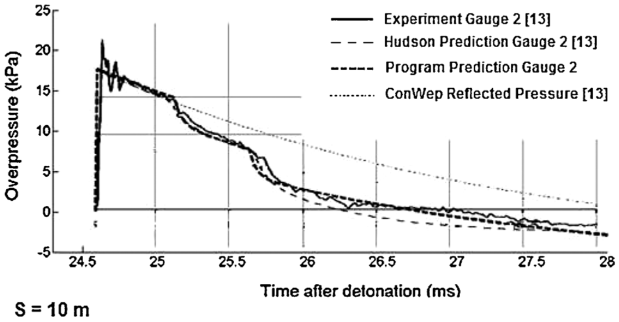

Figure 7. Pressure-time history for G2 at 10 m distance.

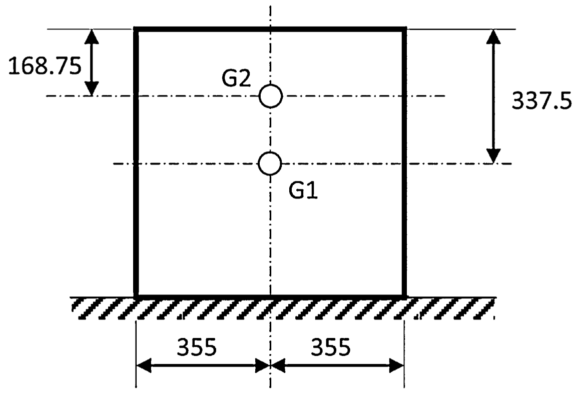

Figure 8. Pressure gauge locations inside the target face [13] (dimensions are in mm).

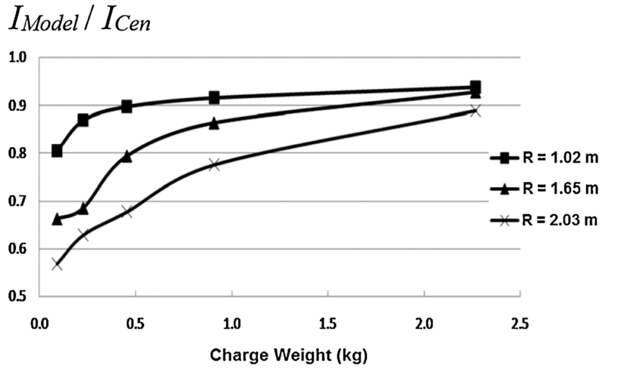

Figure 9. The effect of charge weight on I_{Model}/I_{en} at different standoff distances (R) (plate width w = plate length l = 0.508 m).

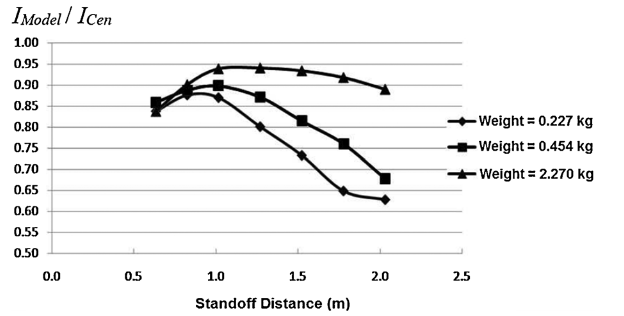

Figure 10. The effect of the standoff distance on I_{Model}/I_{cen} at different charge weights (w = l = 0.508 m).

a ground slab and clad with 20 mm thick mild steel plate to give mounting points for pressure gauges and provide flat, square target faces. The side of the target facing the explosive charge was 675 mm in height and 710 mm in width (Figure 8).

By comparison of the pressure history from the code with the experimental results, a good agreement was observed between them. Also, compared with Hudson's model, the results show that the code can provide the pressure history with good accuracy.

3 Results and Discussion

3.1 Impulse Uniformity Analysis

Impulse distribution on a plate depends on some parameters including charge weight, standoff distance and plate dimensions. Studying resultant parameter serves to answer the question when the impulse distribution acting on a structure can be considered uniform. So, I_{Model} (average impulse considering both wave sphericity and relief wave), I_{sph} (average impulse considering only wave sphericity), and I_{cen} (impulse in the central point of the plate) are compared with each other.

First, the effect of charge weight on impulse distribution was investigated (Figure 9). At each distance (1.02, 1.65, and 2.03 m), the increasing charge weight makes I_{Model} approach to I_{cen} and the impulse will become more uniform. It is because of limiting the duration time of blast wave, which reduces the opportunity for forming and running relief wave from edge to center of the plate such that this reduction affects only the latter part of the pressure history.

As stated in the literature, most researchers believe that the greater distance from the charge is, the more uniform is the blast wave. This is the case, but as shown in Figure 10, the relief wave causes non-uniformity at far distance. In other words, there is an optimal distance, in which the impulses acting on the plate have maximum uniformity. It is due to the fact that an increase in the distance from the charge affords an increase in the duration time of blast wave and provides a greater opportunity for relief wave to influence on the amount of applied impulse. So, firstly, the increasing distance makes the impulse more uniform because blast wave becomes more planar, but from a certain distance to the next, relief wave causes decrease in uniformity.

Figure 11 shows the effect of plate dimensions on the impulse distribution. It can be seen when the plate dimensions are increased, the difference between I_{Model} and I_{sph} is

© 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

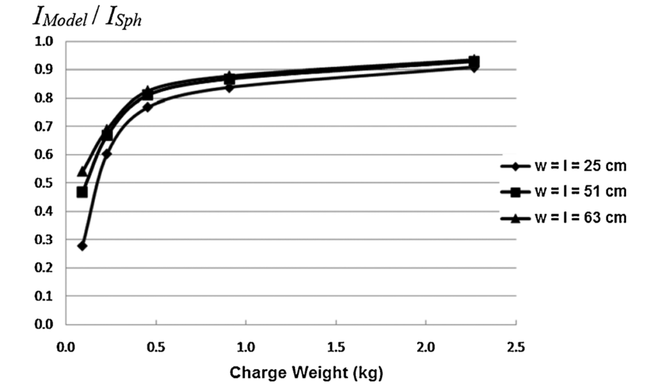

Figure 11. I_{Model}/I_{sph} vs. charge weight at different plate dimensions ($R=1.65$ m).

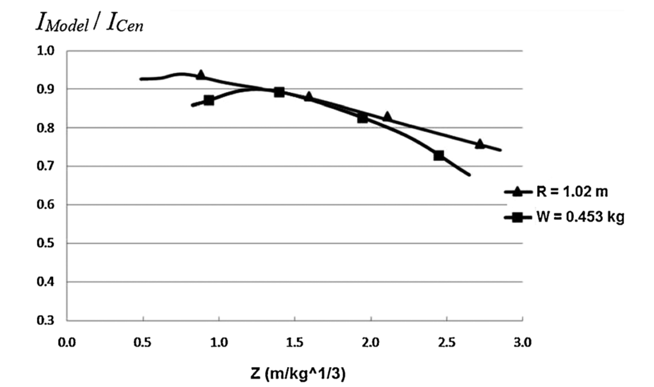

Figure 12. I_{Model}/I_{cen} vs. scaled distance (Z):(a) standoff distance is constant ($R=1.0$ m), and (b) charge weight is constant ($w=0.453$ kg).

declined. In other words, the effectiveness of relief wave is reduced in large structures.

As mentioned in the introduction, some researchers use the scaled distance (Z) as a criterion to determine uniform condition of blast wave, variation of which depends on both charge weight and standoff distance (SOD). Figure 12 shows impulse uniformity vs. variation of Z in two conditions: (a) SOD is fixed ($R=1.02$ m) and only charge weight changes, and (b) charge weight ($W=0.453$ kg) is constant. It is easily seen that depending on which parameter varies, impulse uniformity is different. This result shows that Z is not an appropriate criterion to determine uniform condition.

3.2 Uniform Conditions

To reduce costs and facilitate analyses, it is useful that calculations are performed assuming an uniform wave, but certain conditions must be determined such that the computational error becomes a minimum. According to the results, it is clear that one cannot expect to exactly satisfy uniform condition with simply increasing SOD. In other

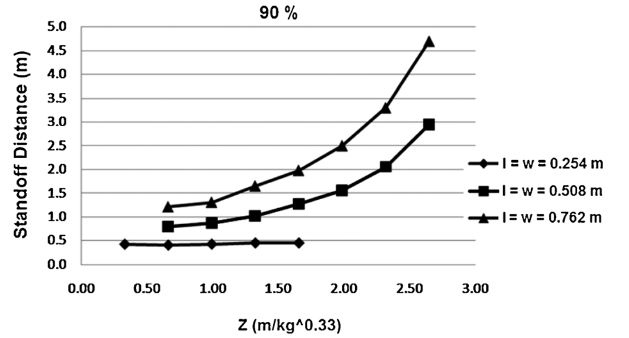

Figure 13. Effective parameters on impulse uniformity; $I_{Model}/I_{cen}=0.90$.

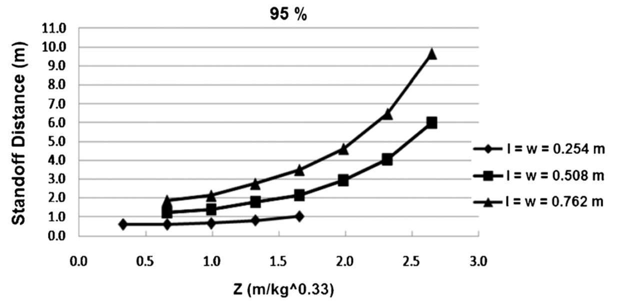

Figure 14. Effective parameters on impulse uniformity; $I_{Model}/I_{cen}=0.95$.

words, all parameters must be simultaneously considered to obtain the best uniform condition.

As shown, the parameters have different effects on relief wave and wave sphericity. As an example, although an increase in the distance affords a more to planar blast wave, it also makes the relief wave more effective and blast wave more non-uniform. Due to the different influences of parameters, applying just a criterion to determine uniform condition in all circumstances is not probably possible.

Although complete uniformity conditions ($I_{Model}=I_{cen}$) are impossible, computational error of uniform impulse assumption can be reduced by proper parameters. At this point, it is suitable to develop, if possible, a representative diagram for uniform conditions in terms of the standoff distance, scaled distance, and plate dimensions (Figure 13). In this diagram, given two optional parameters, the third parameter can be obtained, while I_{Model}/I_{cen} is kept constant at 0.9. In this case, it can be assumed that 90 % of the center point impulse is uniformly impacted on the plate as a whole. It should be noted that the other independent parameter, i.e. charge weight, influences on scaled distance.

Figure 14 can be used when only 5 % difference between I_{Model} and I_{cen} is desired. Comparing Figure 13 and Figure 14, it is clear that the more uniformity is increased, the more the cost is increased.

© 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim

4 Conclusions

The conditions of interaction between blast wave and plate in which the blast wave sphericity and the relief wave influence the applied impulse were studied herein. The results show that the effect of the relief wave on the uniformity of the blast wave can no longer be disregarded, especially for weak shocks, in which the plates are subjected to more non-uniform impulses. Thus, an increase in the distance from the charge or reducing the charge weight causes more pressure relief and therefore a greater difference between I_{Model} and I_{cen}.

Increasing the distance with a constant charge weight makes the blast wave more planar and uniform, but simultaneously, more pressure is relieved from the edges of the plate and causes the imposed impulse to be more non-uniform. Thus, with any charge weight, there is an optimum distance, where the impulse of the blast wave has maximum uniformity.

At each distance, an increasing charge weight affords shorter duration time and there will be less opportunity for pressure relief. Therefore, in this case, the uniform distribution of the impulse is more influenced by the wave sphericity or the plate dimensions.

References

[1] J. Wei, L. R. Dharani. Fracture Mechanics of Laminated Glass Subjected to Blast Loading, *Theor. Appl. Fract. Mech.* **2005**, *44*, 157.

[2] R. L. Veldman, J. Ari-Gur, C. Clum, A. DeYoung, J. Folkert. Effects of Pre-Pressurization on Blast Response of Clamped Aluminum Plates, *Int. J. Impact Eng.* **2006**, *32*, 1678.

[3] *Structures to Resist the Effects of Accidental Explosions*, Department of the Army Technical Manual TM 5-1300/NAVFAC P-397/AFR 88-22, Navy and Air Force, U.S. Department of the Army, Washington D.C., USA, **1990**.

[4] J. R. Florek, *Study of Simplified Models of Aircraft Structures Subjected to Generalized Explosive Loading*, Ph. D. Thesis, Rutgers University, New Brunswick, NJ, USA, **2007**.

[5] D. D. Rickman, D. W. Murrell, Development of an Improved Methodology for Predicting Airblast Pressure Relief on a Directly Loaded Wall, *ASME J. Pressure Vessel Technol.* **2007**, *129*, 195.

[6] S. Glasstone, P. J. Dolan, *The Effect of Nuclear Weapons*, 3rd ed. U. S. Department of Defense and the U.S Department of Energy, Washington D.C., USA, **1977**.

[7] *Fundamentals of Protective Design for Conventional Weapons*, TM 5–855–1, U.S. Department of the Army, Washington D.C., USA, **1986**.

[8] G. F. Kinney, K. J. Graham, *Explosive Shocks in Air*, 2nd ed, Springer-Verlag, New York, **1985**.

[9] W. E. Baker, *Explosions in Air*, University of Texas Press, Austin, TX, USA, **1973**.

[10] T. A. Rose, P. D. Smith, An Approach to the Problem of Blast Wave Clearing on Finite Structures Using Empirical Procedures Based on Numerical Simulations, *16th Int Symposium on Military Aspects of Blast and Shock*, Keble College, Oxford, UK, September 10–15, **2000**, p. 133.

[11] T. A. Rose, P. D. Smith, and J. H. May, The Interaction of Oblique Blast Waves with Buildings, *Shock Waves* **2006**, *16*, 35.

[12] C. C. Hudson, *Sound Pulse Approximations to Blast Loading* (with Comments on Transient Drag), SC-TM-191-55-51, Sandia Corporation Technical Memorandum, Sandia, NM, USA, **1955**.

[13] A. Tyas, J. A. Warren, T. Bennett, S. Fay, Prediction of Clearing Effects in Far-Field Blast Loading of Finite Targets, *Shock Waves* **2011**, *21*, 111.

[14] E. Borenstein, *Loading and Structural Response Models For Transverse Deflection of Circular Plates Subjected to Near Field Explosions*, Ph. D. Thesis, Rutgers University, New Brunswick, NJ, USA, **2010**.

Received: July 29, 2013
Revised: March 30, 2014
Published online: May 23, 2014

© 2014 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim