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A Review of Blast and Impact of Metallic and Sandwich Structures

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ABSTRACT: In blast and impact, structures usually undergo large plastic deformations or failure, and they absorb considerable energy. In this paper, the characteristics of blast loads and corresponding structural response, as well as the current advances in this area, were briefly reviewed. The concept and effects of blast wave, the main means of blast impact, are introduced. Several critical structural responses are classified and briefly illustrated. The major experimental methods were introduced with a brief description of corresponding experimental devices such as ballistic pendulums and a wide range of sensors to measure impulse, pressure and acceleration and displacement of structures. Several commonly used analytical models were presented and compared to estimate the dynamic behaviour of structure under blast loading. The numerical approaches to analyze the structure responses to blast impact were also summarised with a number of available constitutive relations of explosive charge and material properties of structures.

1 INTRODUCTION

Today, the impact resistance of engineering structures subjected to blast and impact is of great interest to engineering communities and government agencies against possible terrorist threats. In the explosion, the peak pressure produced by shock wave is much greater than the static collapse pressure of the structures. The structures usually undergo large plastic deformation and absorb energy before collapsing to a more stable configuration or fracture. A deep insight into the relationship of explosion loads and the structure deformation/fracture behaviour will offer a structure with significantly enhanced energy absorption and blast impact resistance performance.

The energy absorption behaviour of structures and materials has recently been presented comprehensively in a monograph by Lu and Yu (2006). The topics include general methodology of analysis, metallic structural components such as circular and square tubes under various loading, ductile tearing, the dynamic effect of materials and structures, and the performance of composites and cellular solids like honeycombs, metal foams and wood. Several cases are also presented, which bear high relevance to practical civil engineering structures. Another monograph by Jones (1989) is available, which is fully devoted to the structural response to impact loading. In this book, the failure of structures is treated thoroughly, together with experiments and theoretical models.

Given the existence of the two monographs mentioned above, in this paper, we focus our review on the impact response of metallic structures under blast loadings, which has received much research attention recently. The topic is arranged as follows: Section 2 introduces the concept and effects of blast wave, which are the main means of blast impact. Next several critical structural responses are classified and briefly described in Section 3. Sections 4~6 review the current advances in the investigations for blast loading and corresponding structural responses. Finally, a summary is presented in Section 7.

2 BLAST WAVES AND THEIR EFFECTS

The detonation of explosive creates a shock wave in the surrounding air, which is known as a blast wave. Figure 1 (1985) shows a typical pressure-time history for a blast wave, where t_a is the time of arrival of the blast wave, P_s is the peak pressure of the blast wave and P_a is ambient air pressure. The discontinuous pressure rise at the shock front is shown by the jump in pressure from P_a to P_s at time t_a. Figure 1 also shows an approximately exponential decrease in pressure until the pressure drops down to the pre shock level at time t_a+t_d. Apart from P_s and t_a, another significant blast wave parameter is the specific impulse of the wave during the positive phase I_s, as given by

$$I_s = \int_{ta}^{ta+td} P(t)dt \tag{1}$$

where P(t) is overpressure as a function of time.

According to Cole (1948), the blast loading can be qualified based on the charge weight and standoff distance. Generally, the amount of charge of explosive in terms of weight is converted to an equivalent value of TNT weight (known as TNT equivalency) by a conversion factor. In other words, the TNT is employed as a reference for all explosives. Sometimes scaling laws are used to predict the properties of blast waves from large-scale explosions based on tests on a much smaller scale.

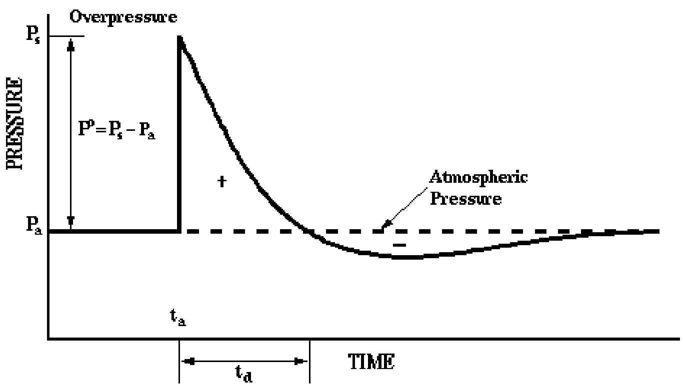

Figure 1. Blast wave pressure-time profile

The most common form of blast scaling is Hopkinson-Cranz or cube-root scaling (Baker *et al*, 1983). It states that self-similar blast waves are produced at identical scaled distances when two explosive charges of similar geometry and of the same explosive, but of different sizes, are detonated in the same atmosphere. It is customary to use as a scaled distance a dimensional parameter, Z, as follows:

$$Z = \frac{R}{W^{1/3}} \tag{2}$$

where R is the distance from the center of the explosive source, and W is the charge mass of TNT.

In some cases, the interaction of a shock with a surface can be quite complex; hence the geometry and the state of the incident shock are very important when studying blast interaction with surfaces. For example, when a shock undergoes reflection, its strength can be increased significantly. The magnification is highly non-linear and depends upon the incident shock strength and the angle of incidence.

3 RESPONSE OF STRUCTURES SUBJECTED TO BLAST LOADS

Explosions of a high explosive usually result in large plastic deformations of structures. The important characteristics of structural response include (1) mode of deformation and fracture, (2) impulse transfer, and (3) energy absorption in plastic deformation. The mode of deformation and facture is the most important characteristic as all the other parameters depend on it.

Generally the methodologies of investigating the structural response include experimental studies, theoretical modeling and numerical simulations. Current advances in these methodologies are reviewed in the subsequent sections.

4 EXPERIMENTAL STUDIES

4.1 Experimental facilities

Based on the nature of the experimental facilities, they can be classified as two types: (1) pendulums and (2) sensors, which are introduced in Sections 4.1.1 and 4.1.2 respectively.

4.1.1 Ballistic pendulums

A ballistic pendulum system can be used to measure impulse imparted to various shock mitigation materials subjected to air blast explosion. With a charge detonated in front of the pendulum, the blast pressure exerted on the pendulum face causes the pendulum to rotate or translate. The displacement at the centre of mass is measured by a linear displacement transducer. The imparted impulse can then be calculated from the measured displacement of the centre of mass and the distance from the rotation/translation centre.

In academia, Enstock & Smith (in press), and Hansen *et al.* (2002) used two-cable pendulums which can be applied to measure the impulse by several kilograms' TNT. Nurick et al. [8] have used four-cable pendulums for small explosive loading studies for a number of years. These two types of pendulums are shown in Figure 2(a) and (b), respectively.

(a) A two-cable pendulum


(b) A four-cable pendulum
Figure 2. Two types of ballistic pendulums

4.1.2 Sensors

Based on the parameters to be measured, sensors used for blast tests are accelerometer, displacement transducer and pressure sensor, as shown in Figure 3. According to different specific requirements, one can choose one or more of them for a test.

(a) Accelerometer

(b) Displacement transducer

(c) Pressure sensor

Figure 3. Some sensors used for blast tests

Jacinto et al. (2001) used pressure sensors and accelerometers to measure the overpressure generated by the high explosive and acceleration of unstiffened steel plates subjected to the impact. Apart from these two sensors, Boyd (2002) also used displacement transducers for his blast experiments. Guruprasad & Mukherjee (2000) conducted experiments to test the impulsive resistance of a sacrificial structure, on which a set of potentiometers were mounted to measure the structural deformation. In the experiments by Neuberger *et al.* (in press, *ibid.*), a comb-like device was applied to measure the dynamic deflections of two thick armor steel plates.

4.2 Deformation and fracture modes observed in experiments

Numerous deformation and fracture modes of structures have been observed in blast experiments, and these studies can be found in several excellent review articles and books (Jones, 1989; Nurik and Martin, 1989; Jones, 1989). Menkes and Opat (1973) conducted blast experiments on clamped beams and were the first to distinguish the three damage modes: (I) Large inelastic deformation; (II) Tearing (tensile failure) at or over the support; and (III) Transverse shear failure at the support. Figure 4 shows the transition from a Mode I to a Mode III with increasing impulsive velocity.

Similar modes were later observed by Teeling and Nurick (1991) for fully clamped circular plates, and Olson *et al.* (1993) and Nurick and Shave (1996) for fully clamped rectangular plates. For Mode I, the extent of damage is described by the amount of residual deflection (Δ). The threshold for Mode II is taken as that impulse intensity which first causes tearing. As the load increases, Modes II and III overlap. A pure, well defined shear failure is characterized by no significant deformation in the severed central section.

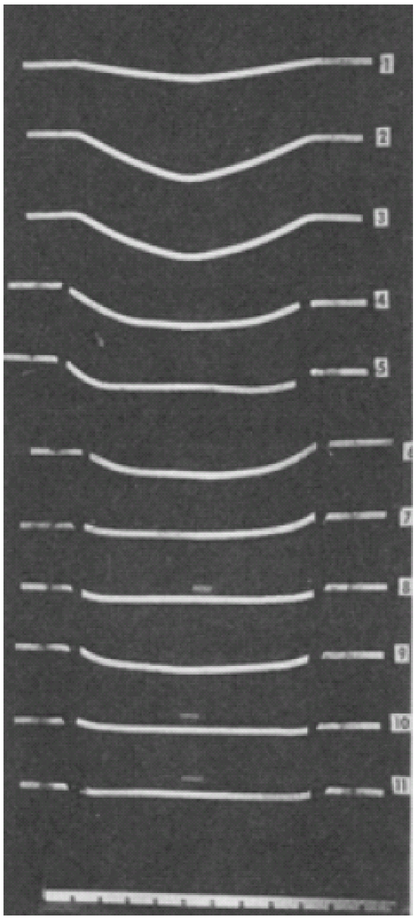

Figure 4. Failure modes of a beam

4.2.1 Large inelastic deformation

Mode I failure of rectangular plates under blast loading has been reported by Yu and Chen (1992), Zhu (1996), Rudrapatna *et al.* (1999) and Ramajeyathilagam *et al.* (2000).

Nurick *et al.* (1996) experimentally studied the thinning (necking) and subsequent tearing at the boundary of clamped circular plates subjected to uniformly loaded air blasts. Mode I was further divided as: Mode I (no visible necking at the boundary); Mode Ia (necking around part of the boundary); and Mode Ib (necking around the entire boundary).

4.2.2 Tearing at the support

Mode II failure is defined as the instant when the maximum strain reaches the failure strain obtained from the quasi-static uniaxial tensile test. The experimental investigations for Mode II failure can be found in the literature (Teeling-Smith and Nurik, 1991; Nurik and Shave, 1996; Olson and Nurink, 1993; Rudrapatna et al, 1999; Ramajayathilagam *et al*, 2000; Nurick et al, 1996; Shen and Jones, 1993)

For square plates, tearing was observed to start at the middle of the boundary and progress along the boundary towards the corners. Hence, some additions to Mode II failure were reported Olsen *et al* (1993): Mode II*: partial tearing at the boundary; Mode IIa: complete tearing with increasing mid-point displacement; and Mode IIb: complete tearing with decreasing mid-point displacement.

Similar failure modes have also been found for the structures other than beams and plates such as stiffened panels (Rudrapatna *et al.*, 2000, Yuen and Nurick, 2005; Langdon *et al.*, 2005)

4.2.3 Transverse shear failure at the support

Mode III is characterised by insignificant flexural deformation at most cross sections, and shear failure occurs at the supports in the early stages of the response and generally exhibits a local response. This type of failure mode was studied by Li & Jones for beams (Li and Jones, 1999) and plates (Li and Jones, 2000), and Cloete *et al.* (2005) for centrally supported structures (Wen et al., 1995). Mode III failure criteria of plastic shear sliding is adopted using a shear strain failure criteria as proposed by Wen et al. (1995) for beams. The parameters of this failure model with respect to the circular plates have been presented by Wen and Jones (1996).

5 THEORETICAL MODELLING

Theoretical or analytical models provide valuable information for locating damage and establishing criteria for acceptance and/or repair of structural components. Analytical solutions that can describe damage would enable one to recognize impact parameters. Parametric studies can then show how the failure of structures varies with impact parameters. Furthermore, analytical solutions provide benchmark solutions for more refined finite element analysis. Nevertheless, most analytical models are complex, as they must involve dynamic, large deformation, plastic deformation of structures.

A review of the relevant literature was given by Jones (1989), and Nurick and Martin (1989). Based on the nature of analytical modelling methodologies, the analytical models can be classified as (1) Single-degree-of-freedom models; (2) Modal approximation models; and (3) Rigid plastic theory based models, which are introduced as follows:

5.1 Single-degree-of-freedom models

Single-degree-of-freedom (SDOF) models, also known as spring-mass models, have been used widely to predict dynamic response of a broad range of structures when subjected to dynamic loads. Response of a SDOF structural model provides fundamental response mode, which is normally responsible for overall structural failure. Parameters used to describe SDOF model are converted from actual structure by using equivalent mass, damping and resistance function (Smith and Heterington, 1994). The equation to describe an SDOF structure is

$$M\ddot{x} + c\dot{x} + Kx = P(t) \tag{3}$$

where M is the structure mass, K is structure resistance, and c is the structure damping coefficient. x and P(t) denote displacement and load respectively. In the case of blasting loading condition, this equation is usually simplified by setting the damping term c to zero because in one cycle of displacement attenuation is small, ignoring c is a conservative approach and for structures taken beyond their elastic limit, energy dissipation is mainly by plastic deformation. An equivalent SDOF structure for a beam subjected to uniform impulsive loads is shown in Figure 5.

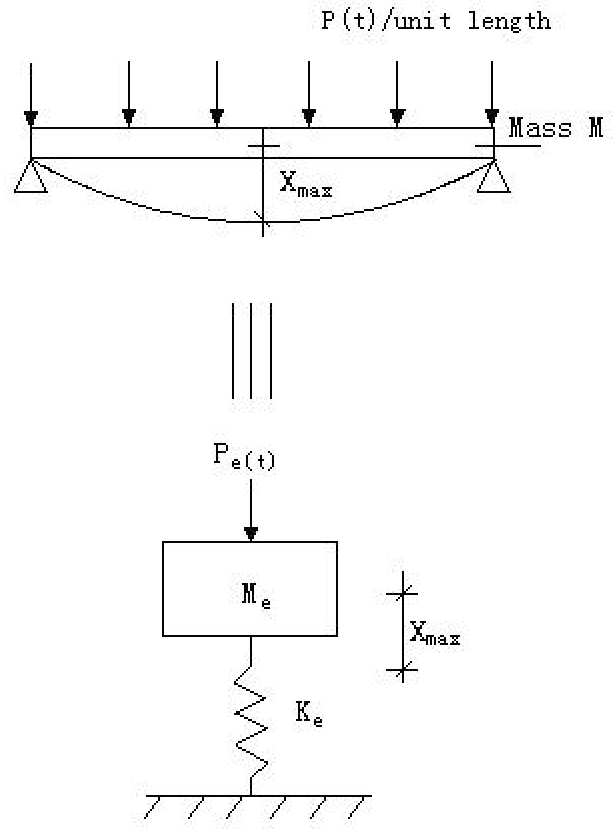

Figure 5. An equivalent SDOF system for a beam

Based on the concept of SDOF systems, Biggs (1964) formulated simple dimensionless design carts (i.e. Pressure-Impulse chart, or P-I chart) to predict the dynamic response of structures in which plastic hinges with full plastic capacity develop. Rigid, perfectly plastic methods were developed and reasonable correlation with test results were achieved, provided that the peak load is much higher than the maximum resistance and the loading regime is impulsive. Similar studies can be found in the papers by Symonds (1953), Hodge (1956), Youngdahl (1970), Abrahamson and Lindberg (1976), and Li and Meng (1998).

5.2 Modal approximation models

Modal solutions are of fundamental importance for explaining and estimating the deformation of structures that develop in response to impact or blasting loading. For either rigid-perfectly plastic or rigid-strain hardening structures that are given a heavy blow over a segment of the structure, the deformation that develops divides into an initial transient phase where the pattern or location of deformation is continually changing, and a modal phase where the pattern is constant. During the transient phase the pattern of deformation steadily evolves from the initial velocity distribution imposed at impact to a mode configuration. After attaining the velocity distribution of a stable mode configuration, the pattern of deformation remains constant for some period of time. In most cases a substantial part of the impact energy is dissipated in a mode configuration during the second phase of deformation (Stonge and Yu, 1993).

Work by Symonds (Symonds, 1980; Symonds, 1980) including the effects of elastic deformations and large deflections in the analysis of structures subjected to pulse loading using approximate theoretical techniques has been demonstrated for fully clamped beams of mild steel. Symonds (Symonds, 1980; Symonds, 1980) used a modelling technique which confines elastic effects entirely to an introductory stage (no plastic deformation) and to a residual vibration after plastic deformation. Elastic deflection components are ignored during plastic deformation. A plate model proposed by Yankelevsky (1985) incorporates rigid segments interconnected by plastic hinge lines which produce a displacement field typically used for collapse mechanisms in yield line theory of reinforced concrete slabs. The approaches proposed by Schleyer and Hsu (2000) and Schleyer *et al.* (2003) differed from the approach used by Symonds and Yankelevsky by combining elastic deflection components and plastic deformations in each stage of the analysis and by solving the equilibrium equations numerically. Wierzbicki & Nurick (1996) used the momentum conservation approach and eigenvalue expansion method to derive an approximate modal solution for large transient deformations of plates subjected to central explosive loading. Based on this method, Lee and Wierzbicki (2005) and Wang and Hopkins (1954) further proposed modal solutions for the three stages of the failure of thin clamped circular plates loaded by localized shock impact, namely dishing, discing and petalling.

5.3 Rigid plastic theory based models

Based on the rigid plastic theory, Wang and Hopkings 1954) and Symmonds (1954) analysed the response of clamped axisymmetric plates and beams, respectively subjected to impulsive loads. Both these studies were restricted to linear bending kinematics with in-plane stretching neglected. Jones (1989) extended the analysis of Symmonds (1954) by giving an approximate solution for the response of clamped beams under finite deflections.

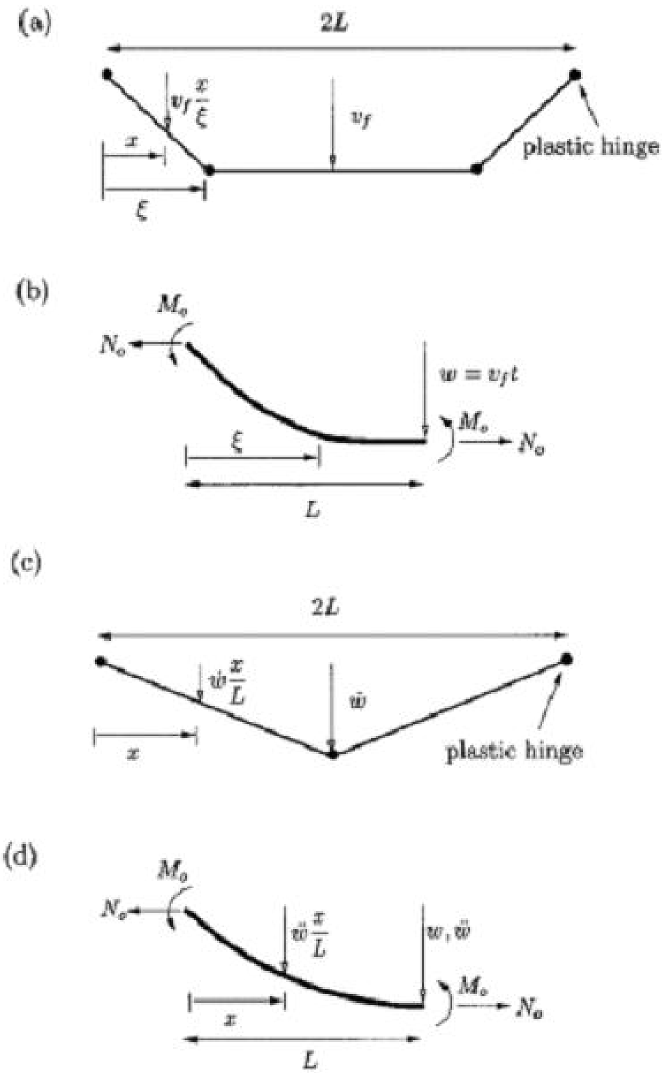

Figure 6. Analysis of stage III of the blast response of sandwich structures

Based on the model by Jones (1989), Fleck *et al.* (2004); Qui et al. (2004), Radford and Fleck (2006) recently developed a series of analytical models, to predict the dynamic response of sandwich structures under a uniform shock loading Fleck and Deshphande (2004) or a non-uniform one over a central patch (Radford *et al*. 2006; Qiu *et al.*, 2005). The sandwich structures comprise steel face-sheets and cellular solid cores, with ends fully clamped. The response to shock loading is measured by the permanent transverse deflection at the mid-span of the structures. The structural response of the sandwich structures can be split into three sequential stages: Stage I: This is actually a 1D air-structure interaction process during the blast event, resulting in a uniform velocity of the outer face-sheet; Stage II: The core crushes and the velocities of the faces and core become equalized by momentum sharing; and Stage III: This is the retardation stage at which the structure is brought to rest by plastic bending and stretching. The problem under consideration here is turned into a classical one for monolithic beams or plates, which has been extensively studied and presented in Jones (1989). Figure 6 shows a typical plastic hinges travelling process of a plate in stage III of the blast response loaded by a uniform impulsive impact.

6 NUMERICAL SIMULATIONS

Since blast tests can be very expensive and dangerous, finite elements analysis (FEA) offers the possibility to evaluate response of the impulsively loaded structures using commercial software packages such as ABAQUS and LS-DYNA. FEA has the capability of predicting distribution of internal stress and strains that are difficult to be measured experimentally. Also FEA can be employed to understand how structures fail and to identify critical parameters.

The following sub-sections will discuss the approaches of modelling the blast loads and the material properties from which the structures are made.

6.1 Modelling blast loads

6.1.1 Defining the pulse-time curve directly

The idea of directly defining the pulse-time curve is quite straightforward and may be the easiest way to model blast loads. However, the coupling effects of the loads and structures, such as the change of structural curvature and shock wave reflections, are not considered. Therefore, sometimes the simulation performance of this method is not satisfactory.

6.1.2 Defining blast loads using blast pressure functions

The blast loads can be conveniently calculated using blast pressure functions such as ConWep (1991), which was developed by the US Army. The ConWep function can produce non-uniform loads exerted on the top surface of the plates. This blast function can be used for two cases: free air detonation of a spherical charge, and the ground surface detonation of a hemispherical charge. The input parameters include equivalent TNT mass, type of blast (surface or air), detonation location, and surface identification for which the pressure is applied. The pressure is calculated based on the following equation:

$$P(\tau) = P_{\mathrm{r}} \cdot \cos^2\theta + P_i \cdot (1+\cos^2\theta - 2\cos\theta) \qquad (1\text{-}4)$$

where θ is the angle of incidence, defined by the tangent to the wave front and the target's surface, P_{r} is the reflected pressure, and P_i is the incident pressure. It can be seen that ConWep calculates the reflected pressure values and applies them to the designated surfaces by taking into account the angle of incidence of the blast wave. It updates the angle of incidence incrementally and thus account for the effect of surface rotation on the pressure load during a blast event.

The drawback of ConWep is that it cannot be used to simulate the purely localized impulsive loads produced by explosive flakes or prisms. Some simulations using ConWep can be found in the literature (Yen et al., 2005; Neuberger et al, in press).

6.1.3 Modelling the explosive as a material

In this method, the explosive is modelled as a material. When the explosive is detonated, its volume expands significantly and interacts with the structure. The contact force between the expanded explosive product and structure is then calculated. The expansion of the explosive is defined by three parameters: position of the detonation point, burn speed of the explosive and the geometry of the explosive.

The explosive materials are usually simulated by using Jones-Wilkins-Lee (JWL) high explosive equation of state, which describes the pressure of the detonation (Haliquist, 1998). The JWL equation is written as

$$P = A\left(1-\frac{\omega\rho}{R_1\rho_0}\right)e^{-R_1\frac{\rho_0}{\rho}} + B\left(1-\frac{\omega\rho}{R_2\rho_0}\right)e^{-R_2\frac{\rho_0}{\rho}} + \frac{\omega\rho^2}{\rho_0}E_{m0} \qquad (5)$$

where P is the blast pressure, ρ is the explosive density, ρ_0 is the explosive density at the beginning of detonation process, A, B, R_1, R_2, ω, and E_{m0} are material constants, which are related to the type of explosive and can be found in the explosive handbooks.

6.2 Modelling materials

Engineering structures subjected to blast impact can be made of monolithic materials or cellular solids. A number of constitutive relations are available to describe their dynamic behaviour under blast loading conditions.

6.2.1 Modelling monolithic materials

Two commonly used material models for metals are introduced here.

The Johnson-Cook material model is a widely used constitutive relation, which describes plasticity in metals under strain, strain rate, and temperature conditions (Halliquist, 1998).

$$\sigma_y = (A + B\bar{\varepsilon}^{p^n})(1 + c\ln\dot{\varepsilon}^*)(1 - T^{*m})$$
(6)

where A, B, C, m and n are used defined material constants; $\bar{\varepsilon}^p$ is effective plastic strain; $\dot{\varepsilon}^* = \dot{\bar{\varepsilon}}^p / \dot{\varepsilon}_0$, being effective plastic strain rate, for $\dot{\varepsilon}_0 = 1\mathrm{s}^{-1}$; $T^* = (T\text{-}T_{room})/(T_{melt}\text{-}T_{room})$. The constants for a variety of materials are found in (Johnson and Cook, 1997).

If only the strain rate effect is considered, the above model is equivalent to another famous material model, namely the Cowper-Symonds relation, in which the strain rate is calculated for time duration from the start to the point, where the strain is nearly constant from the equivalent plastic strain time history (1989). In the Cowper-Symonds model, the dynamic yield stress (σ_{dy}) can be computed by

$$\sigma_{dy} = \sigma_y \left(1 + \left| \frac{\dot{\varepsilon}}{D} \right|^{1/n} \right)$$
(7)

where σ_{dy} is the static yield stress and D and n are material constants.

6.2.2 Modelling cellular solids

Cellular solids such as metal forms and honeycombs can absorb considerable energy by plastic dissipation in compression. Their cellular microstructure endows them with the ability to undergo large deformation at nearly constant nominal stress (Gibson and Ashby, 1997; Hansen *et al.*, 2002). Therefore, they have been used as the cores of sandwich structures to absorb impacts and shocks.

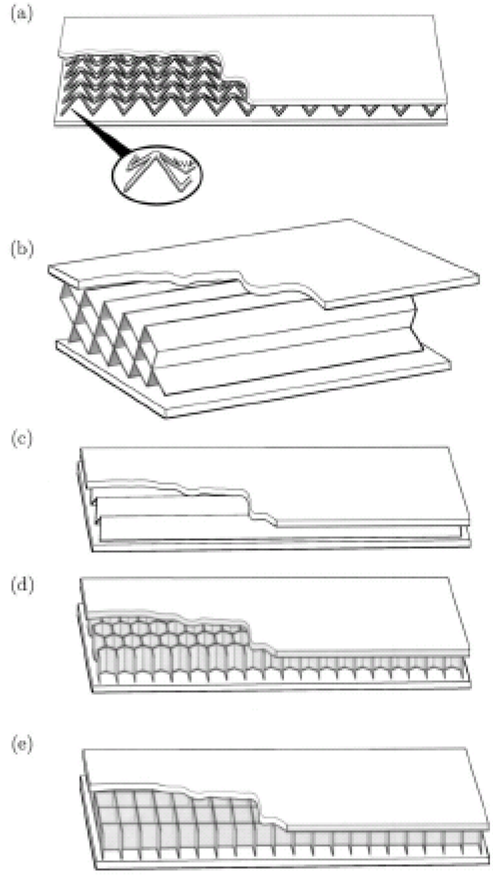

Figure 7. Sketches of the sandwich core topologies; (a) pyramidal core, (b) diamond- celled core, (c) corrugated core, (d) hexagonal-honeycomb core, and (e) square-honeycomb core

A detailed review of constitutive models for metal foam applicable to structural impact and shock analyses has been presented by Hanssen *et al.* (2002). The models have different formulations for the yield surface, hardening rule and plastic flow rule, while fracture is not accounted for in any of them.

In recent years a number of micro-architectured materials have been developed for uses as the cores of novel sandwich structures for application in blast-resistant construction. The current available topologies are shown in Figure 7: pyramidal core, diamond-celled core, corrugated core, hexagonal-honeycomb core, and square-honeycomb core (Fleck and Deshpande, 2004).

The relative mechanical properties of the cores are assumed to be made from an elastic, ideally-plastic solid with yield strain ε_Y. Their normalised transverse compressive strength $\bar{\sigma}_n$ and longitudinal strength $\bar{\sigma}_l$ were predicted in Xue and Hutchinson (2004).

7 SUMMARY

In blast impact, structures usually undergo large plastic deformations or failure, and they absorb considerable energy. In this paper, the characteristics of blast loads and corresponding structural response, as well as the current advances in this area, were briefly reviewed.

The detonation of explosive creates a blast wave in the surrounding air, and interacts with the structures. The resulting structural response is divided into three modes: (I) Large inelastic deformation; (II) Tearing (tensile failure) at or over the support; and (III) Transverse shear failure at the support. Mode I can transit to Mode II and III with the increase of impulsive loads.

The approaches to investigating blast loads and corresponding structural response can be experimental, analytical or numerical. In experiments, one can use ballistic pendulums and a wide range of sensors to measure impulse, pressure and structural responses, such as acceleration and displacement.

Analytical models provide valuable information for locating and quantifying damage, and establish criteria for different deformation/failure modes. The commonly used analytical models include (1) Single-degree-of-freedom models; (2) Modal approximation models; and (3) Rigid plastic theory based models. In a SDOF model, the actual structural response is described by using an equivalent spring-mass system. Modal approximation modelling method divides the deformation into an initial transient phase where the pattern or location of deformation is continually changing and a modal phase where the pattern is constant. In the rigid plastic theory based approach, the deformation is also divided into stages and the structure is assumed to be made of a rigid plastic material.

Numerical simulation techniques such as FEM have the capability of predicting distribution of internal stress and strains that are difficult to be measured experimentally, and help to understand how structures fail and to identify critical parameters. In the simulations, the blast loads can be modelled using an impulse-time curve or blast pressure function. Alternatively, one can model the high explosives as special materials, and the interaction between expanded explosives and structures can be further calculated. The structures subjected to the blast impact are usually made of monolithic metals or cellular solids. A number of constitutive relations are available to describe their mechanical behaviours with the effects of strain, strain rate and/or temperature.

REFERENCES

Abrahamson, G.R., and Lindberg, H.E., (1976) Peak load-impulse characterization of critical pulse loads in structural dynamics, *Nuclear Engineering Design*; 37: 35-46.

Ashby, M.F., Evans, A., Fleck, N.A., Gibson, L.J., Hutchinson, J.W., Wadley, H.N.G., (2000) Metal foams: a design guide, Butterworth-Heineman, Oxford.

Baker, W., Cox, P., Westine, P., Kulesz, J. and Strehlow, R. (1983) Explosion hazards and evaluation, Elsevier, New York.

Biggs, J.M. (1964) Introduction to structural dynamics, McGraw-Hill, New York.

Boyd, S.D., (2002) Acceleration of a plate subject to explosive blast loading – Trial results. *Internal Report DSTO-TN-0270;* Department of Defence, Australia.

Cloete, T.J., Nurick, G.N., and Palmer, R.N. (2005) The deformation and shear failure of peripherally clamped centrally supported blast loaded circular plates, *International Journal of Impact Engineering*; 32: 92-117.

Cole, R.H. (1948) Underwater explosions. Dover, New York.

CONWEP (1991) – Conventional Weapons Effects program, Version 2.00; US Army Engineer Waterways Experimental Station, Vicksburg, MS, USA.

Enstock, L.K., and Smith, P.D., Measurement of impulse from the close-in explosion of doped charges using a pendulum, *International Journal of Impact Engineering*, In press.

Fleck NA, Deshpande VS. (2004) The resistance of clamped sandwich beams to shock loading. *Journal of Applied Mechanics*, ASME; 71: 1-16.

Gibson, L.J., and Ashby, M.F. (1997) Cellular solids: structure and properties (2nd edition), Cambridge University Press, Cambridge.

Guruprasad, S., and Mukherjee, A. (2000) Layered sacrificial claddings under blast loading Part II – experimental studies, *International Journal of Impact Engineering*; 24: 975-984.

Hallquist, J.O., LS-DYNA (1998) theoretical manual, Livermore software technology Co.; Livermore, CA, USA.

Hanssen, A.G., Enstock, L., and Langseth, M (2002) Close-range blast loading of aluminium foam panels, *International Journal of Impact Engineering*; 27: 593-618.

Hanssen, A.G., Hopperstad, O.S., Langseth, M. and Ilstad, H. (2002) Validation of constitutive models applicable to aluminium foams, *International Journal of Mechanical Sciences*; 44: 359-406.

Hodge, P.G. (1956), The influence of blast characteristics on the final deformation of circular cylindrical shells. *Journal of Applied Mechanics*; 23: 617-624.

Jacinto, A.C., Ambrosini, R.D. and Danesi, R.F. (2001) Experimental and computational analysis of plates under air blast loading, *International Journal of Impact Engineering*; 25: 927-947.

Johnson, G.R., and Cook, W.H. (1983) A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures, *Proceedings of the 7th International Symposium on Ballistics*; The Hague, The Netherlands.

Jones, N. (1989) Structural Impact. Cambridge University Press, UK.

Jones, N. (1989) Recent studies on the dynamic plastic behaviour of structures, *Applied Mechanics Review*; 42(4): 95-115.

Kinney, G., and Graham, K. (1985) Explosive shocks in air, 2nd Ed, Springer-Verlag, New York.

Langdon, G.S., Yuen, S.C.K., and Nurick, G.N. (2005) Experimental and numerical studies on the response of quadrangular stiffened plates. Part II: localised blast loading, *International Journal of Impact Engineering*; 31: 85-111.

Lee, Y.W., and Wierzbicki, T. (2005) Fracture prediction of thin plates under localized impulsive loading. Part I: dishing, *International Journal of Impact Engineering*; 31: 1253-1276.

Lee, Y.W., and Wierzbicki, T., (2005)Fracture prediction of thin plates under localized impulsive loading. Part II: discing and petalling, *International Journal of Impact Engineering*; 31: 1277-1308.

Li, Q.M., and Jones, N. (2000) Formation of shear localization in structural elements under transverse dynamic loads, *International Journal of Solids and Structures*; 37: 6683-6704.

Li, Q.M., and Jones, N. (1999) Shear and adiabatic shear failures in an impulsively loaded fully clamped beam, *International Journal of Impact Engineering*,; 22: 589-607.

Li, Q.M., and Meng, H. (2002) Pulse loading shape effects on pressure-impulse diagram of an elastic-plastic, single-degree-of-freedom structural model, *International Journal of Mechanical Sciences*; 44: 1985-1998.

Lu, G., and Yu, TX (2003) Energy Absorption of Structures and Materials. Woodhead, Cambridge, UK. (*Its Chinese edition is published by Chemical Industry Press*, Beijing, China, 2006)

Menkes, S.B., and Opat, H.J. (1973), Tearing and shear failures in explosively loaded clamped beams, *Experimental Mechanics*; 13: 480-486.

Neuberger, A., Peles, S. and Rittel, D., Scaling the response of circular plates subjected to large and close-range sperical explosions. Part I: Air-blast loading, *International Journal of Impact Engineering*, In press.

Neuberger, A., Peles, S. and Rittel, D., Scaling the response of circular plates subjected to large and close-range sperical explosions. Part II: Buried loading, *International Journal of Impact Engineering*, In press.

Nurick, G.N., and Martin, J.B. (1989) Deformation of thin plates subjected to impulsive loading – A review Part I: Theoretical considerations, *International Journal of Impact Engineering*; 8(2): 159-170.

Nurick, G.N., and Martin, J.B. (1989) Deformation of thin plates subjected to impulsive loading—a review, Part II: Experimental Studies, *International Journal of Impact Engineering*; 8(2): 159-170.

Nurick, G.N., and Shave, G.C. (1996) The deformation and tearing of thin square plates subjected to impulsive loads – an experimental study, *International Journal of Impact Engineering*; 18(1): 99-116.

Nurick, G.N., Gelman, M.E., and Marshall, N.S. (1996) Tearing of blast loaded plates with clamped boundary conditions, *International Journal of Impact Engineering*; 18(7-8): 803-827.

Olson, M.D. Nurick, G.N., Fagnan, J.R. (1993) and Levin, A., Deformation and rupture of blast loaded square plates – predictions and experiments. *International Journal of Impact Engineering*; 13(2): 279-291.

Qiu X, Deshpande VS, Fleck NA. Dynamic response of a clamped circular sandwich plate subject to shock loading, *Journal of Applied Mechanics, ASME*; 71: 637-645.

Qiu X, Deshpande VS, Fleck NA. (2004) Impulsive loading of clamped monolithic and sandwich beam over a central patch. *Journal of the Mechanics and Physics of Solids*, 2005; 53: 1015-1046.

Radford DD, Fleck NA, Deshpande VS. (2006) The response of clamped sandwich beams subject to shock loading. *International Journal of Impact Engineering*; 32: 968-987.

Ramajeyathilagam, K., Vendhan, C.P., and Bhujanga Rao, V. (2000) Non-linear transient dynamic response of rectangular plates under shock loading, *International Journal of Impact Engineering*; 24: 999-1015.

Rudrapatna, N.S., Vaziri, R., and Olson, M.D. (1999) Deformation and failure of blast-loaded square plates, *International Journal of Impact Engineering*; 22: 449-467.

Rudrapatna, N.S., Vaziri, R., and Olson, M.D. (2000) Deformation and failure of blast-loaded stiffened plates, *International Journal of Impact Engineering*; 24: 457-474.

Schleyer, G.K, and Hsu, S.S. (2000) A modelling scheme for predicant the response of elastic-plastic structures to pulse pressure loading, *International Journal of Impact Engineering*; 24: 759-777.

Schleyer, G.K., Hsu, S.S., White, M.D., and Birch, R.S. (2003) Pulse pressure loading of clamped mild steel plates, *International Journal of Impact Engineering*; 28: 223-247.

Shen, W.Q., and Jones, N. (1993) Dynamic response and failure of fully clamped circular plates under impulsive loading, *International Journal of Impact Engineering*; 13: 259-278.

Smith, P.D., Heterington, J.G. (1994) Blast and ballistic loading of structures, Butterworth-Heinemann Ltd., Oxford.

Stronge, W.J., and Yu, T.X. (1993) Dynamic models for structural plasticity, Springer-Verlag, London.

Symmonds, P.S. (1954) Large plastic deformation of beams under blast type loading, *Proceedings of the Second US National Congress of Applied Mechanics*; 505-515.

Symonds, P.S. (1953) Dynamic load characteristics in plastic bending of beams, *Journal of Applied Mechanics*; 20: 475-481.

Symonds, P.S. (1980) Elastic, finite deflection and strain rate effects in a mode approximation technique for plastic deformation of pulse loaded structures, *Journal of Mechanical Engineering Science*; 22(4): 189-197.

Symonds, P.S. (1980) Finite elastic and plastic deformations of pulse loaded structures by and extended mode technique, *International Journal of Mechanical Sciences*; 22(10): 597-605.

Teeling-Smith, R.G., and Nurick, G.N. (1991) The deformation and tearing of thin circular plates subjected to impulsive loads, *International Journal of Impact Engineering*; 11(1): 77-91.

Wang, A.J., and Hopkins, H.G. (1954) On the plastic deformation of built-in circular plates under impulsive load, *Journal of Mechanics and Physics of Solids*; 3: 22-37.

Wen, H.M., and Jones, N. (1996) Low velocity perforation of punch-impact loaded metal plates, *Journal of Pressure Vessel Technology*, Transactions of ASME; 118(2): 181-187.

Wen, H.M., Yu, T.X., and Reddy, T.Y. (1995) Failure maps of clamped beams under impulsive loading, *Mechanics Based Design of Structures and Machines*; 23: 453-472.

Wierzbicki, T., and Nurick, G.N. (1996) Large deformation of thin plates under localized impulsive loading, *International Journal of Impact Engineering*; 18: 899-918.

Xue, Z., and Hutchinson, J.W. (2004) A comparative study of blast-resistant metal sandwich plates, *International Journal of Impact Engineering*; 30: 1283-1305.

Yankelevsky, D.Z. (1985) Elastic-plastic blast response of rectangular plates, *International Journal of Impact Engineering*; 3(2): 107-119.

Youngdahl, C.K. (1970) Correlation parameters for eliminating the effect of pulse shape on dynamic plastic deformation, *Journal of Applied Mechanics*; 37: 744-752.

Yu, T.X., and Chen, F.L. (1992) The large deflection dynamic plastic response of rectangular plates, *International Journal of Impact Engineering*; 12(4): 603-616.

Yuen, S.C.K., and Nurick, G.N. (2005) Experimental and numerical studies on the response of quadrangular stiffened plates. Part I: subjected to uniform blast load, *International Journal of Impact Engineering*; 31: 55-83.

Zhu, L. (1996) Transient deformation models of square plates subjected to explosive loadings, *International Journal of Solids and Structures*; 33(3): 301-314.