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 $P_a$ and $t_a$, another significant blast wave parameter is the specific impulse of the wave during the positive phase $I_s$, as given by

$$I_s = \int_{t_a}^{t_a+t_d} P(t)dt$$

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 stand-off distance. Generally, the amount of charge of explosive in terms of weight is converted to an equiva-
lent 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.

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:

\[
Z = \frac{R}{W^{1/3}}
\]

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 fracture 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 two-cable pendulum](image1)

![A four-cable pendulum](image2)
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.

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.

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 approxima-

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

\[ M \ddot{x} + c \dot{x} + Kx = P(t) \]

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 charts (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 Hopkins (1954) and Symonds (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 Symonds (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
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 apherical 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:

\[ P(\tau) = P_i \cdot \cos^2 \theta + P_i \cdot (1 + \cos^2 \theta - 2 \cos \theta) \]  (1-4)

where \( \theta \) is the angle of incidence, defined by the tangent to the wave front and the target's surface, \( P_i \) 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

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

where \( P \) is the blast pressure, \( \rho \) is the explosive density, \( \rho_0 \) is the explosive density at the beginning of detonation process, \( A, B, R_1, R_2, \omega, \) and \( E_{m0} \) are material constants, which are related to the type of ex-
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 (Hallquist, 1998).

\[
\sigma_y = (A + B\varepsilon^p)(1 + c \ln \dot{\varepsilon}^*)(1 - T^{*m})
\]

(6)

where \( A, B, C, m \) and \( n \) are used defined material constants; \( \varepsilon^p \) is effective plastic strain; \( \dot{\varepsilon}^* = \varepsilon^p / \dot{\varepsilon}_0 \), being effective plastic strain rate, for \( \dot{\varepsilon}_0 = 1 \text{s}^{-1} \); \( T^* = (T - T_{\text{room}})/(T_{\text{melt}} - T_{\text{room}}) \). 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 \( (\sigma_{dy}) \) can be computed by

\[
\sigma_{dy} = \sigma_y \left( 1 + \left| \frac{\dot{\varepsilon}^*}{D} \right|^{n/2} \right)
\]

(7)

where \( \sigma_{dy} \) is the static yield stress and \( D \) and \( n \) are material constants.

6.2.2 Modelling cellular solids

Cellular solids such as metal foams 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.

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-architected 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 \( \varepsilon_Y \). Their normalised transverse compressive strength \( \tilde{\sigma}_n \) and longitudinal strength \( \tilde{\sigma}_l \) 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.

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