Sandwich Plates Loaded at Explosion Impact

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This paper presents the results of a study concerning the protective capacity of ship hull structures made of sandwich composite materials subject to an explosion impact. The main application of these structures lies in design of ship structures of great importance, which should also be protected against exceptional loads of this kind. A nonlinear analysis with the finite-element computer code COSMOS/M was done. The methodology for the blast pressure charging and the mechanism of the blast wave in free air are given. The spatial pressure variation is determined by using Friedlander exponential decay equation. Various scenarios (parametric calculus) to evaluate the behavior of the ship structure sandwich plate to blast loading are presented: explosive magnitude, distance from source of explosion, plate thickness.

Keywords: Sandwich plates, composites, blast loads

Following the different accidental or intentional events, blast loads induced by explosion within or immediately nearby ship hull can cause catastrophic damage on the ship structure and shutting down of critical life safety systems. Loss of life and injuries to crew and passengers can result from many causes, including direct blast-effects, structural collapse, debris impact, fire and smoke [1]. To provide adequate protection against explosions, the design and construction of ship hull are receiving renewed attention of structural engineers. Difficulties that arise with the complexity of the problem, which involves time dependent finite deformations, high strain rates, and non-linear inelastic material behaviour, have motivated various assumptions and approximations to simplify the models.

Transient response of the shells from ship hull structures to high intensity loads is often investigated in the context of sonic booms, explosive blasts, and other shock type pressure loads. Sonic booms and explosions that are initiated sufficiently far from a structure are often idealized as pressure waves arriving at all points on the structure's surface simultaneously.

In close proximity to an explosion, the ship hull structures are loaded by a high intensity-short duration pressures that vary in time and space.

Most part of the literature available concerning plate response to short-duration, high intensity pressures make this assumption. Experimental evidence supporting this assumption is provided in [2]. In many of these works, the time history of the spatially uniform pressure is described by step-pulse, N-pulse, or Friedlander equations [3].

Finite element modelling and analysis for the blast-loaded cylindrical shell are also presented in [4 - 6]. Kinematically admissible displacement functions are chosen to represent the motion of the clamped cylindrical shell and the governing equations are obtained in the time domain using the Galerkin method.

The particular equation used for the pressure-time history of the load is often chosen to best match the particular phenomenon; considered. The time history of overpressures due to explosions is often represented by the modified Friedlander exponential decay equation [7].

The work presented here focuses on the structural response to such close proximity explosions. In particular, the structures considered include sandwich composite and contacting plates subject to mine blasts. Both linear and nonlinear solution are developed for these simulations.

Idealisation of blast loading

Simulation of blast loading and estimation of structure behaviour and damage under blast loading are very important phase of research to evaluate the resistance and safety of hull structure against direct and consequential blast damage.

The pressure time-history of a blast wave can be illustrated with a general shape as in Fig. 1. The illustration is an idealization for an explosion in free field. The pressure time-history is divided into a positive and a negative phase.

Explosion dissipates energy forming light, sound, and very dense and high pressure wave with initial expansion at very high velocities.

Typical explosive detonations in the free field create a suddenly rising and rapidly decaying pressure to satisfy equilibrium with surrounding environment, or a shock wave with very short duration.

The range in which the risen pressure decays back to normal pressure is defined as a positive phase (see figure 4). As the wave front expands, a negative pressure phase occurs when the pressure is lower than ambient pressure. The negative phase has a small effect on the response of structures.

In the positive phase, maximum overpressure is developed instantaneously and decays to atmospheric pressure in the time T_0. For the negative phase, the maximum negative pressure has much lower amplitude than the positive overpressure.

The duration of the negative phase, is much longer compared to the positive duration. The positive phase is more relevant in studies of blast wave effects on structures because of its high amplitude of the overpressure and the concentrated impulse, which is the area under the positive phase of the pressure – time curve.

Impulse is a measure of the energy from an explosion imparted to a building. Both the negative and positive phases of the pressure-time wave form contribute to impulse. The magnitude and distribution of blast loads on a structure vary greatly with several factors.

An universal normalized description of the blast effects can be given by scaling distance relative to $(E/P_0)^{1/3}$ and

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scaling pressure relative to P_0, where E is the energy release (kJ) and P_0 the ambient pressure (typically 100 kN/m^2). For convenience, however, it is general practice to express the basic explosive input or charge weight W as an equivalent mass of TNT. Results are then given as a function of the dimensional distance parameter (scaled distance)

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

where R is the actual effective distance from the explosion and W is generally expressed in kilograms. Scaling laws provide parametric correlations between a particular explosion and a standard charge of the same substance.

Blast wave parameters for conventional high explosive materials have been the focus of a number of studies during the 1950's and 1960's. Estimations of peak overpressure P_{so} (in kPa) due to spherical blast based on scaled distance Z, were introduced in [8] as:

- for $P_{so} > 1000$ kPa

$P_{so} = 670 / Z^3 + 100,$

- for $10 < P_{so} < 1000$ kPa

$P_{so} = 97.5 / Z + 145.5 / Z^2 + 585 / Z^3 - 1.9$

The shape of blast wave can be represented by linear decay using an approximate triangular equivalents or more realistic exponential decay shown in figure 1 based on Friedlander equation which intends to agree with experimental values of blast pressure [1]. A modified Friedlander's equation is as follows

$$p(t) = p_{so}\left(1-\frac{t-T_a}{T_0}\right)e^{-A\left(\frac{t-T_0}{T_0}\right)} \tag{2}$$

where $p(t)$ is blast pressure at time t, p_{so} is peak incident pressure, T_0 is positive phase duration, T_a is arrival time, and A is a decay coefficient.

Peak reflected pressure is given as a function of variables such as peak incident pressure, angle of wave incidence to the surface of an object and shock front velocity etc. Then, reflected impulse proportional to the calibrated peak reflected pressure and the corresponding duration of reflected pressure will be determined [5].

In accordance with above mentioned references the overpressure associated with the blast pulses can be described in terms of the modified Friedlander exponential decay equation [1], as

$$p_y(s,z,t) = p_m\left(1-\frac{t}{t_p}\right)e^{-\frac{a't}{t_p}} \tag{3}$$

where the negative phase of the blast is included. In Eq. (3), p_m denotes the peak reflected pressure in excess of the ambient one; t_p denotes the positive phase duration of the pulse measured from the time of impact of the structure and a' denotes a decay parameter which has to be adjusted to approximate the overpressure signature from the blast tests.

As concerns the sonic-boom loading, this can be modeled as an N-shaped pressure pulse arriving at a normal incidence. Such a pulse corresponds to an idealized far field overpressure produced by an aircraft flying supersonically in the earth's atmosphere or by any supersonic projectile rocket or missile. The overpressure signature of the N-wave shock pulse can be described by

$$p(s,z,t) = \begin{cases} p_m\left(1-\dfrac{t}{t_p}\right) & for\ 0<t<rt_p \\ 0 & for\ t<0\ or\ t>rt_p \end{cases} \tag{4}$$

Once the blast distance is known, elements within 45 degrees of the blast normal vector are divided into groups based upon their average distance to the center node.

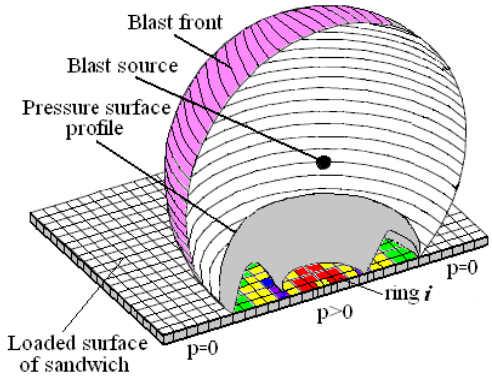

Fig. 1. Model of the spherical blast load wave

In this paper the application of a blast load to a finite element mesh is described. Only elements within the 45 degree cone are loaded. The area within the cone is divided into a number of rings to determine the pressure acting on the elements of the mesh.

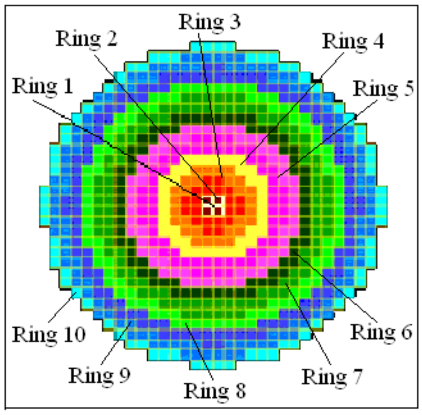

Fig. 2. Distribution of the blast pressure on the sandwich plate surface

According to the methods used in this paper an individual pressure-time history to each element based on its distance from the blast is assigned. Each ring from figure 2, has its own pressure-time history as it is shown in figure 4.

In the application, described in this paper, a rectangular sandwich plate having the side dimension of 500mm was used. The sandwich plate is made of two skins made of E-glass/polyester and a core of 10 mm made of COREMAT.

The material characteristics of the skins, determined in experimental tests (using stretching machine and strain gauges) are ([9-11]):

E_x=38.6GPa, E_y=8.27GPa, E_z=8.27GPa,

G_{xy}=4.14GPa, G_{xz}=4.14GPa, G_{yz} =4.6GPa;

μ_{xy}=0.3, μ_{yz}=0.42, μ_{xz}=0.3;

R_x^T=1.062 GPa, R_x^C =0.610 GPa, R_y^T =0.031 GPa, R_y^C =0.118 GPa, R_{xy} =0.72 GPa.

The mechanical characteristics of the COREMAT are ([12-15]):

E_x=0.8GPa, E_y=0.8GPa, G_{xy}=0.035GPa; μ_{xy}=0.25

For the studied plate, ten discretization rings were used to load the panel with the mine blast at the distance *h*. Parametric calculus was done for equivalent TNT mass (W=0.1kg, 0.2kg and 0.5kg) placed at the distance *h*=0.2m from the plate surface. The modality to calculate the pressure on the plate is described in figures 2 and 3. The spatial distributions and pressure profiles are illustrated in figure 4 (the ring 1 is the ring placed in the middle of the plate). As it is shown in the figure, the time of arrival, T_a is 0.01s and T_0 is equal to 0.01s.

Modal analysis

The dynamic analysis was done with automatic time stepping. The loading function shown in figure 4 is scaled such that p_{max} = 260 kPa. In order to study the effect of time duration, four time intervals T_0 have been used in this study 1 ms, 2 ms, 10 ms and 20 ms. A modal analysis has been done to obtain the natural frequencies of the plates for determining the ratio of the duration of the loading over the natural period of the structure.

Dynamic analysis

Effect of time duration is a special analysis done in this work. For all models increasing the time duration by factors of 2, 10, and 20 results in an increase in the mid-point displacement by a factor of 1.73; 3.06, and 3.4, respectively.

One important point should be noted, if the time duration T_0 is longer than fundamental semi-period T_i / 2 then the maximum deformation occurs during the pulse phase, while, on the other hand, if T_0 is less than T_i / 2, the maximum deformation occurs during the free vibration phase and is mainly controlled by the time integral of the pulse.

The FEM parametric calculus [16] was done for 3 groups of values for: equivalent TNT mass *W* (0.1 kg, 0.2 kg and 0.5 kg), blast normal distance vector *h* (0.15m, 0.2m and 0.25m) and for total thickness of the composite plate (6.3mm, 12mm and 21mm). For all cases the calculus was done so for material without damping and for damping material according to the equation

$$C = 0.1K + 0.1M \quad (5)$$

Time variation of the maximum von Mises stress obtained in the point placed on the middle of the side plate are presented in figure 3 (material with damping characteristics) and figure 5 (material without damping characteristics) for the plate with total thickness of 21 mm.

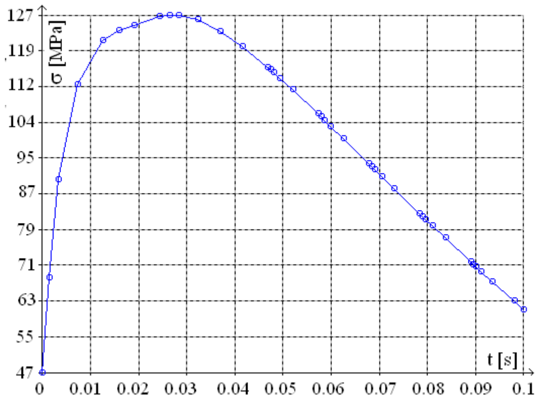

Fig. 3. Maximum von Mises stress on the sides of the sandwich plate with damping

As it is seen, the maximum stress in the case of damping is 2.5 times bigger than the stress in the case of the plate without damping.

Conclusions

A non-linear dynamic finite element analyses were done to examine the behaviour of fully-fixed sandwich plate under blast loading. As was examined, the effect of thickness value can be very important, since it can affect drastically the overall behaviour of the plate.

The time duration is one of the most important parameter since it has an influence on other parameters of the blast loading.

According to the parametric calculus, the material damping model used in the analysis leads to the decreasing of the maximum stress occuring in the plate up to 0.5 from the value obtained in the model without damping. For example, in the figure 6 the variation of maximum stress versus equivalent TNT mass *W* for core thickness of 6.3mm and blast normal distance *h* of 0.25mm for the both cases of damping is presented.

In all analyzed cases, for equivalent TNT mass *W* lesser than 0.2 kg, the stress obtained in the plate is almost constant, for various distances *h* and various plate thicknesses *t*.

The blast wave is instantaneously increases to a value of pressure above the ambient atmospheric pressure. This is referred to as the side-on overpressure that decays as the shock wave expands outward from the explosion source. After a short time, the pressure behind the front may drop below the ambient pressure (fig. 4). During such a negative phase, a partial vacuum is created and air is sucked in. This is also accompanied by high suction winds that carry the debris for long distances away from the

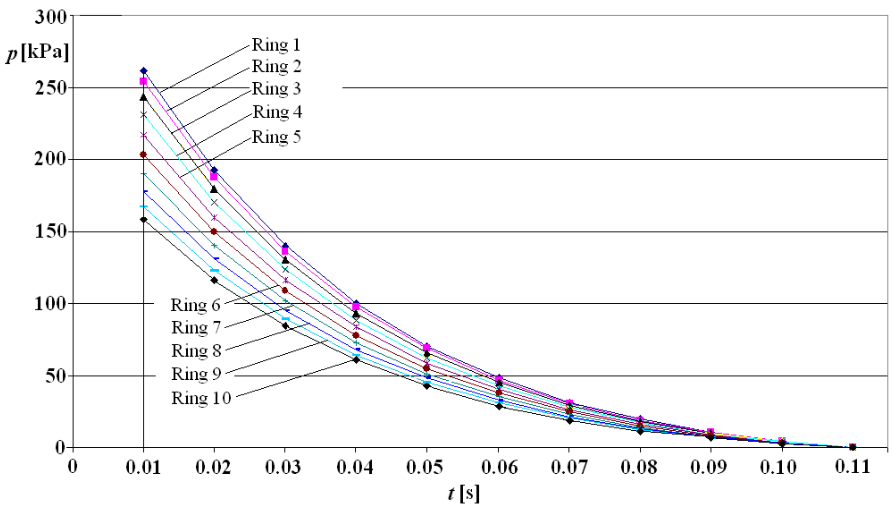

Fig. 4. Variation of pressure on each ring

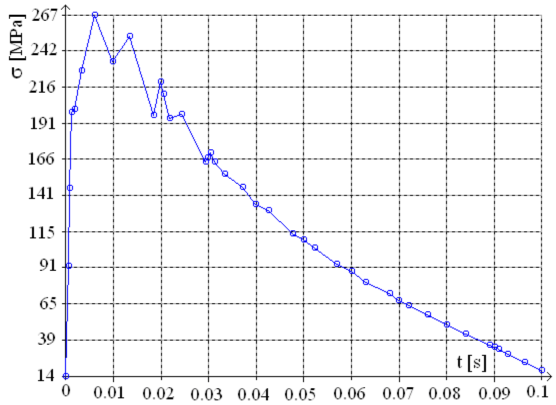

Fig. 5. Maximum von Mises stress on the sides of the plate without damping

explosion source. In the paper this phase is considered as equal to zero. The values of the pressure acting on the plate have small differences for W=0.1kg and W=0.2 kg.

For the values of the equivalent TNT mass W lesser than 0.7 kg, the fails do not occur in the material and so the integrity of the plate is not affected.

According to the analysis, the developed blast simulation model and optimal design system can enable the prediction, design and prototyping of blast-protective sandwich composite structures for a wide range of damage scenarios in various blast events, ranging from plate damage, localized structural failure. From the studies, the proposal of a sandwich composite structure with special damping system can help the structure to sustain blast load. The inclusion of a damping material in the core of the sandwich composite structure can absorb energy under blast load and help to reduce the force transmitted to the main structure. Also, the damping material helps to reduce stress concentration in the sandwich plate material.

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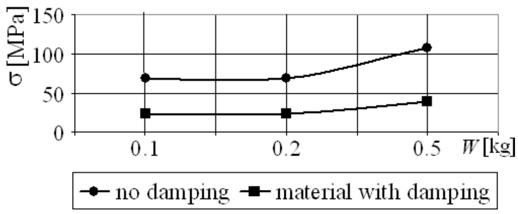

Figure 6. Variation of maximum stress versus equivalent TNT mass W, for t=6.3mm; h=0.25mm

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