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Numerical Investigation of Composite Structures under Blast Loading

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Abstract

In this paper, the behavior of composite structures against the explosive phenomenon has been investigated using finite element method. Some composite shells such as composite plates and hemispheres with different layer-uppinghave been investigated using LS-DYNA software. The blast loading is simulated by explosion's pressure versus time curves and is directly defined in LS-DYNA software. The Tsai-Wu failure criterion is used to predict the behavior of the composite structure.In this paper, the effect of layer-upping on the blast resistance of the structure is investigated. The results show that, hemisphere composite has better performance against the blast loading than plate and failure occur under greater load. Also it is shown that angle ply composite structures has good resistance in comparison with cross plies one.

1. Introduction

Composite structures are important in different areas of industry such as aero, marine aircrafts, ships, automotive and so on. Many of the structures experience blast loading during war or terrorist attack or accidental explosions. Response of composite structures subjected to explosion has been a field of intense activity of researchers in recent decades. So composite plates and shells form one of the basic elements of the structures, therefore, studying the blast response of such structures helps understanding and improving their blast resistance. There are too many papers dealing with the blast loading on the structures. Rajendran [1] investigated the plate behavior under the blast loading. In this review paper, he focuses on the phenomenological evolution of blast damage of plates.

Arora et al. [2] studied the resistance of glass-fiber reinforced polymer(GFRP) sandwich panels and laminate due blast in air and underwater environments. They used an experimental method to obtain the behavior of the plates. The dynamic response and blast behavior of metallic sandwich-walled hollow shells with graded aluminum foam cores are investigated by Liu [3]. They used finite element simulations to model the blast and compared results with those of conventional ungraded ones. Fallah et al [4] studied the dynamic response of a blast-resistant lightweight fiber composites structure alternative to steel for military applications. The results of localized air-blast loading on structure are reported and analyzed by using experimental and numerical methods. A theoretical method is used to predict the large deflection response of fully clamped rectangular sandwich plates subjected to blast loading by Qin et al. [5]. They used energy dissipation balance theory and obtained the solutions for the dynamic response of rectangular sandwich plate. A multi-layered composite structure that made of layers of aluminum alloy AA 7075 bonded with toughened epoxy resin is investigated for blast resistant applications By Johnson et al. [6]. The performance of the proposed thick composite plate made of thick AA 7075 layers, was numerically studied under localized impulsive loading. In the other article represented by Logdon et al [7] the influence of material properties on the response of plates subjected to air-blast loading is investigated using an experimental method. They obtained the failure of mild steel, armor steel, aluminum alloy and fiber reinforced polymer composite plates experimentally by detonating disks of plastic explosive at small stand-off distances. Imbalzano et al [8] investigated sandwich panels composed of axenic cellular cores and metal facets are for blast resistance applications. The performance of this hybrid composite structure under impulsive loading is numerically studied, taking into account the rate-dependent effects and Johnson–Cook law is used to model the behavior of composite materials at high strain rates. Zhu and Khanna [9] represented a numerical model that is developed to simulate the dynamic response of the laminated glass-composite panel under blast loading. They validated the simulated model, in terms of the midpoint deflection, correlates well with the experiments conducted in a blast load simulator. Auora et al [10] presented experimental investigation on the influence of stand-off distance on the dynamic response of thin ductile plates subjected to air blast loading. The square plates were manufactured from two different materials, i.e., medium-strength steel and low-strength aluminum. Low energy impact and post impact behavior of epoxy matrix-woven flax fabric composites are investigated by Papanicolaou et al. [11]. The progressive damage due to increased impact energy levels was studied as a function of impact energy. Johnson et al. [12] studied a multi-layered composite by hierarchical structure made of layers of aluminum alloy AA 7075 bonded with toughened epoxy resin for blast resistant applications. Hazratiet et al. [13] investigated a numerical approach to predict failure in the reinforced V-shape plates subjected to blast loading.

In the present study, the behavior of composite structures such as plates and spherical shells has been investigated using LS-DYNA software. The stress field and time response of the structure is presented. The Tsai-Wu failure criterion is used to predict the strength of the structure due to impulse loading. The results are shown in good graphical and tabular forms to understand the behavior of the composite structure in blast loading.

2. Blast loading

The explosion is a sudden phenomenon that release high values of the energy in a short time. The pressure-time diagram for an explosion is shown in Figure 1. It is seen in this figure that, the pressure is high in first but decrease during time. It is obvious that the modelling of the explosion is very complicate so there are some experimental relations that describe this occurrence. One of the most famous relations of the blast pressure is suggested by the Graham and Kenni as bellows [14]:

$$\frac{p_{\mathrm{so}}}{\mathrm{p_o}} = \frac{808\left[1+\left(\frac{\mathrm{z}}{4.5}\right)^2\right]}{\sqrt{1+\left(\frac{\mathrm{z}}{0.048}\right)^2}\sqrt{1+\left(\frac{\mathrm{z}}{1.35}\right)^2}\sqrt{1+\left(\frac{\mathrm{z}}{0.32}\right)^2}} \tag{1}$$

In which:

$$z = \left(\frac{R}{\sqrt[3]{W}}\right) \tag{2}$$

Where W is the mass of the explosive material and R is the distance. AlsoP_{so} is the maximum pressure and $P_{\mathrm{o}}$is atmospheric pressure.

The destruction of an explosion is measured by the impulse function which is the area underneath the pressure curve. There is an empirical function based on above mentioned pressure function for impulse as bellows [15]:

$$I = \int p dt \tag{3}$$

In which I is the impulse of the explosion. An empirical relation is used to calculate this parameter as below [15]

$$\frac{\mathrm{I}}{\sqrt[3]{\mathrm{W}}} = 6895\left(\frac{0.06076}{\mathrm{z}}+\frac{0.02770}{\mathrm{z}^2}+\frac{0.002945}{\mathrm{z}^3}\right) \qquad 0.4337 \le \mathrm{z} \le 9.1020 \tag{4}$$

In this article the blast loading on the structure is simulated as an approximate function as [16]:

$$P(t) = p_m\left(1 - t/t_p\right)e^{-\alpha t/t_p} \tag{5}$$

In which α, t, t_p are wave parameters, time and positive pressure time, respectively. The eq. 5 is plotted in figure 2.

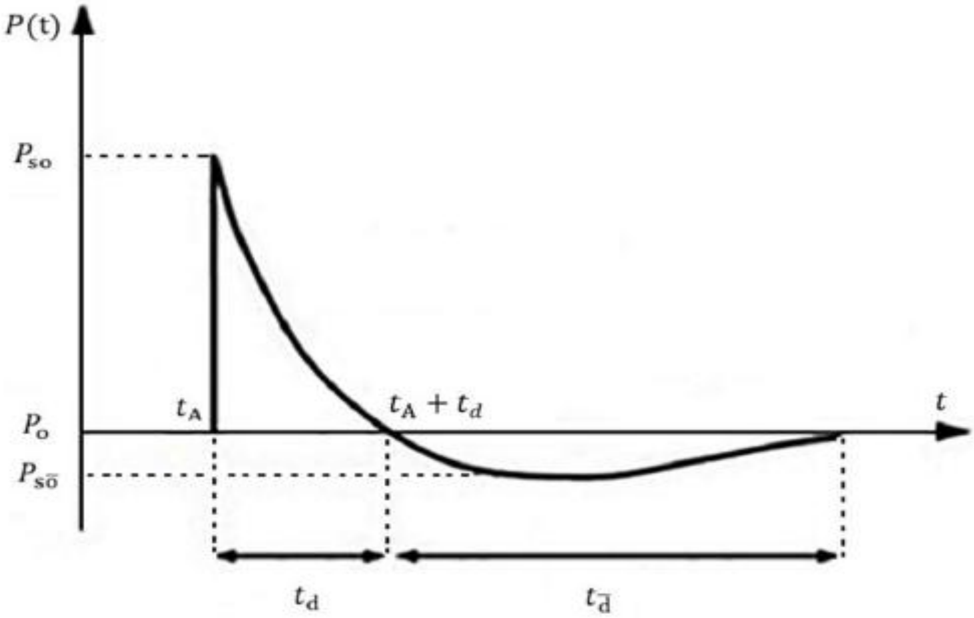

Figure 1: Pressure versus time based on Eq. 5 and parameter definitions

3. Numerical modeling and failure criteria

3.1 Finite element modelling

In this paper the structure is modeled using finite element method and blast loading as eq. 5.In this paper explicit LS-DYNA software is used to solve the nonlinear equation of the motion. At first the model is created by using ANSYS software and the final model is imported in LS-DYNA to solve by the explicit solver. The Tetrahedral solid elements are used in LS-DYNA software to model the structure. This element has 8 nodes and formulated by the linear interpolation functions. This element has 6 faces. Each of the nodes had 3 degree of freedom for displacements in directions *x*, *y* and *z*. this element has other degree of freedoms such as thermal, magnetic and so on but in our analysis only the displacement degrees of freedom are exploited. This element is selected because of its accuracy and meshing the entire domain without any error. The composite layer is consists of 4 layer and each layer is modeled by 3 elements in thickness direction. Also between the layers the automatic surface to surface contact is modeled to avoid any breaking down of the elements. The 19200 and 21960 elements are used for modeling of composite plate and half sphere respectively. These numbers of elements are selected to obtain good accuracy of the results. The thickness of the structure is to be 17 cm. Figure 2 shows the mesh of sphere.

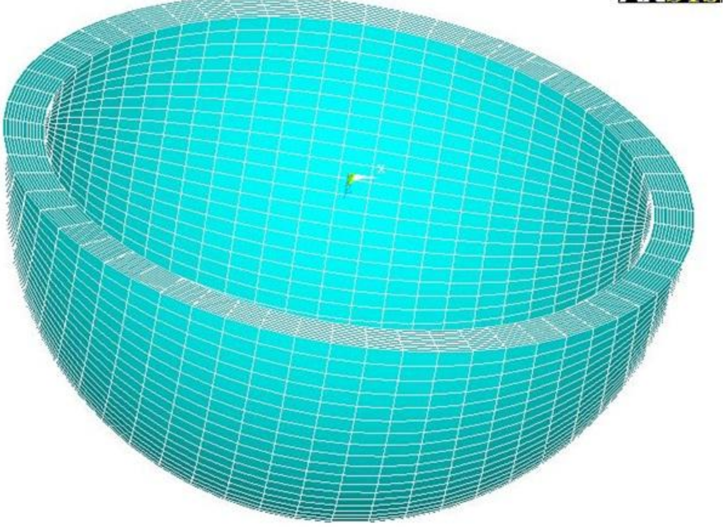

Figure 2: The mesh of the half sphere

3.2. Failure criteria for composite material

LS-DYNA software used various failure criteria for composites. In this paper Tsai-Wu failure criterion is used to simulate the damage of the elements. This failure model based on Beltrami strains rupture energy. In this method it is assumed that the lamina is safe when [17]:

$$H_1\sigma_1 + H_2\sigma_2 + H_6\tau_{12} + H_{11}\sigma_1^2 + H_{22}\sigma_2^2 + H_{66}\tau_{12}^2 + 2H_{12}\sigma_1\sigma_2 < 1 \tag{6}$$

In which:

$$H_1 = \frac{1}{(\sigma_1^T)_{ull}} - \frac{1}{(\sigma_1^c)_{ull}} \tag{7}$$

$$H_{11} = \frac{1}{(\sigma_1^T)_{ull}\,(\sigma_1^c)_{ull}} \tag{8}$$

$$H_2 = \frac{1}{(\sigma_2^T)_{ull}} - \frac{1}{(\sigma_2^c)_{ull}} \tag{9}$$

$$H_{22} = \frac{1}{(\sigma_2^T)_{ull}\,(\sigma_2^c)_{ull}} \tag{10}$$

$$H_6 = 0 \tag{11}$$

$$H_{66} = \frac{1}{(\tau_{12}^T)^2{}_{ull}} \tag{12}$$

$$H_{12} = -\frac{1}{2(\sigma_1^T)^2{}_{ull}} \tag{13}$$

The materials properties of the composite layer that is used in this article are listed in Table 1.

Table 1: Material properties of composite laminate [17]

$(\sigma_1^c)_{ull}$ (MPa)	$(\sigma_1^T)_{ull}$ (MPa)	$(\sigma_2^c)_{ull}$ (MPa)	$(\sigma_2^T)_{ull}$ (MPa)	τ_{12}^T (MPa)
1200	1500	250	50	70

4. Results and discussions

4.1 Composite plates under blast loading

In the first case a composite plate with the laminate sequencing [0-0-0] is investigated exposed to blast loading. The loading is equal to 34.2 gram TNT explosion and explosive material distance from the plate is 20 cm. This is the basic loading and in future cases it is mentioned by this concept. The Figure 3 shows the deflection of the composite plate due to basic blast loading. By increasing the explosive material to 1.9 times of basic value, the plate starts to fail because of the loads. The occurrence of this phenomenon is seen in Figure 4 by the deviation of elements from each other. In the second case, the composite plate by [0-90-0] layer sequencing is investigated. It is seen that in this type of layer sequencing, the final failure load is increased to 1.95 times of basic loading. The Figure 5 shows the rupture of the composite plate.

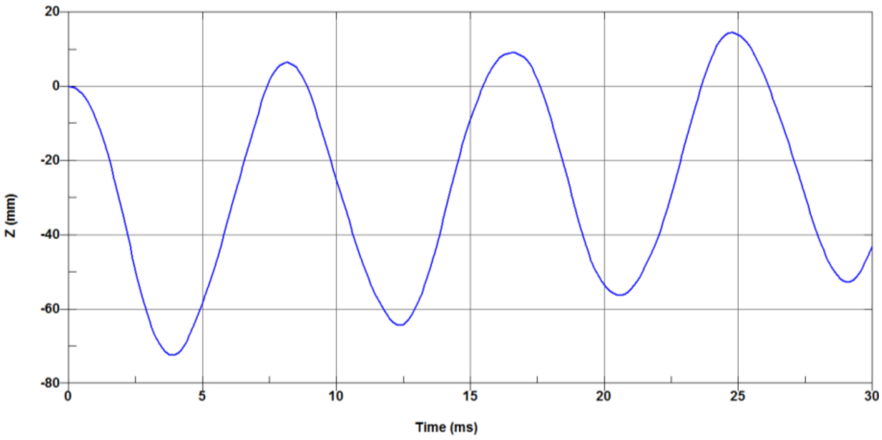

Figure 3: Displacement of plate center due to basic blast loading.

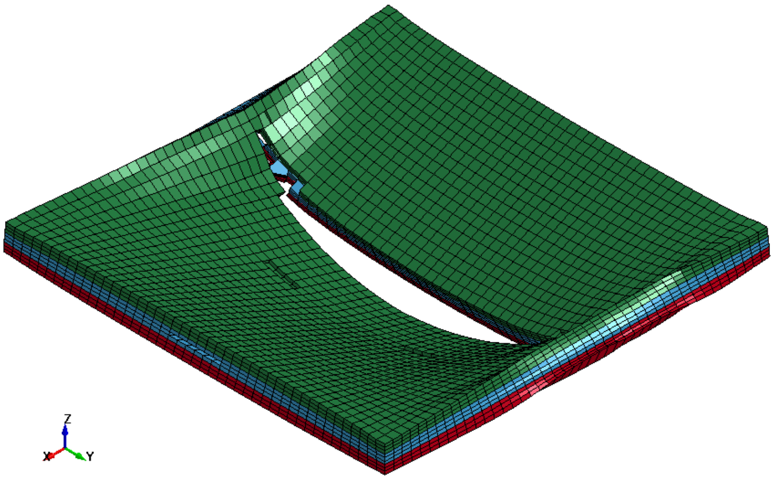

Figure 4: Failure of the [0-0-0] composite plate due to 1.9 times of the basic blast load

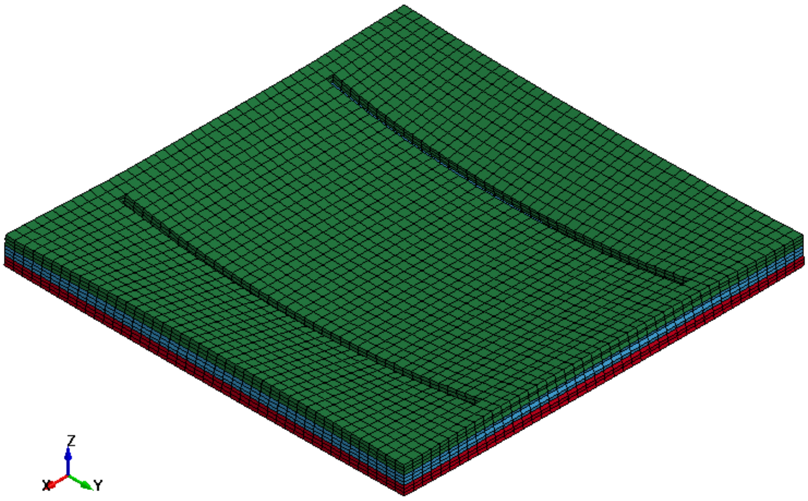

Figure 5: Failure of the [0-90-0] composite plate due to 1.95 times of the basic blast load

From Figures 4-5 it is inferred that the cross ply laminate has more resistance than single ply composite. In the third case, the blast loading is applied to the angle ply laminate $[0\text{-}30\text{-}60\text{-}90]_s$. The analysis shows that in this layer upping, the load to rupture of the plate is 2.05 times greater than the basic loading. So cross ply composites can resist more than angle ply in blast loading.

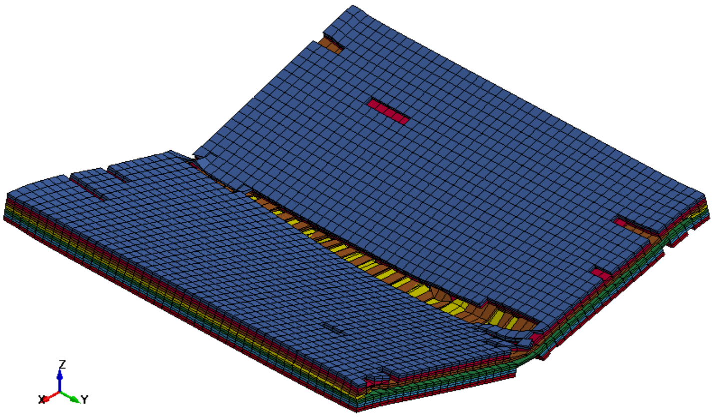

Figure 6: Failure of the $[0-30-60-\overline{90}]_s$ composite plate due to 2.05times of the basic blast load

4.2 composite spherical shells under blast loading

In this section, the response of the composite spherical and cylindrical shells under blast loading is investigated. The meshof the shells are presented in Figures 2. Figure 7 shows the top point deflection of the sphere with layer upping [0-90-0] versus time. The loading is equal to 1 time of reference loading. Figure 8 shows the Von-Mises stress in the sphere in the 11 times of reference loading. It is obvious that the stress is high in the top of the shell. By increasing the load, it is seen that the failure of the shell is occurred when the loading is 12 times of reference loading. Figure 9 shows the failed structure in the blast loading. It is obvious that the top point of the sphere begin to fail during loading.

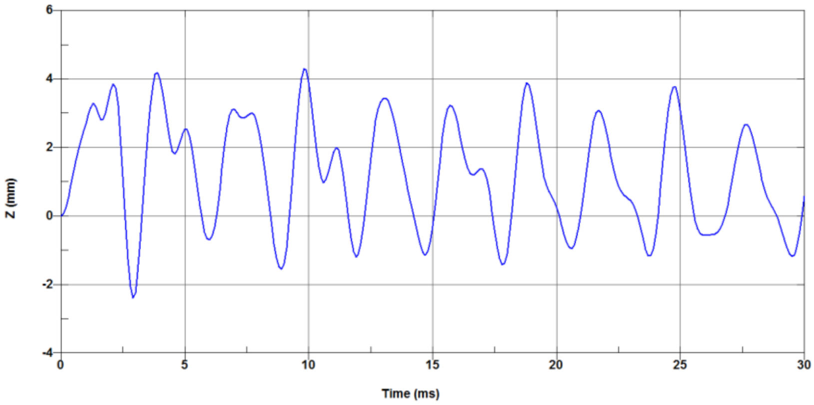

Figure 7: Deflection of the top point of the sphere versus time in reference loading.

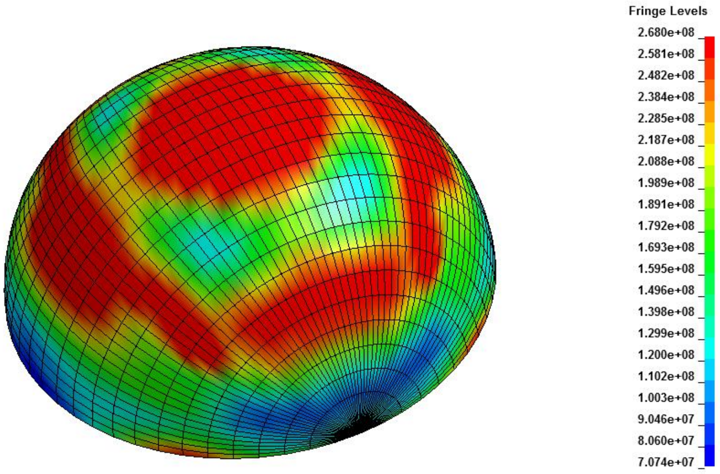

Figure 8: distribution of the Von-Mises stress in the shell

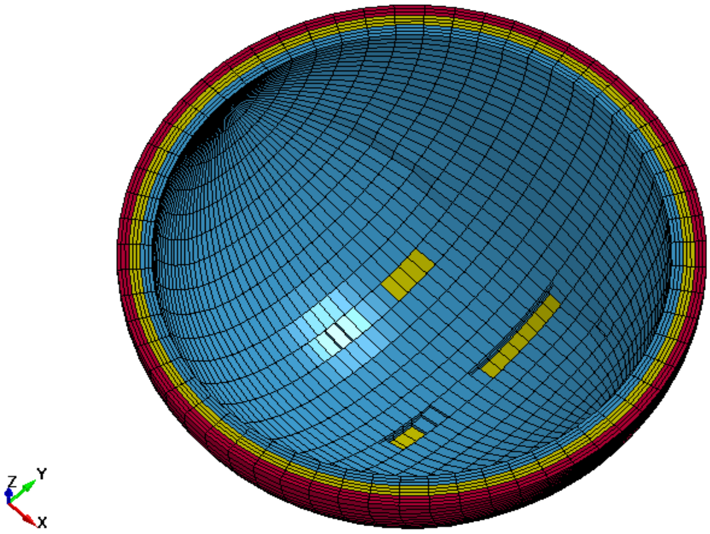

Figure 9: Failure of the shell during blast loading

Conclusions

In the present study, the behavior of composite structures under blast loading is investigated using finite element method. Theblast pressure curve has been defined to LS-DYNA software directly and all analysis has been done with this simplification and structure's resistance against blast loading is investigated. The Tsai-Wu failure criterion is employed to predict thestrength of the composite structure. The stress field and time response of the structure is presented and Tsai-Wu failure criterion is exploited to investigate the strength of the structure due to this type of loading. The results show that hemisphere composite shell under the same load has better resistance against blast in comparison with the plates in the same thicknesses. Also it is inferred that the angle ply layer upping has good resistance from cross ply layer upping in the blast loading and fails at bigger values of explosive material.

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