The 4th International Conference
"Advanced Composite Materials Engineering "
COMAT 2012
18- 20 October 2012, Brasov, Romania

STRENGTH ANALYSIS OF THE SHIP DECK DELAMINATED PLATES AT EXPLOSIONS

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Abstract: *In the paper a nonlinear FEM analysis on the protective capacity of ship hull structures made of laminated composite materials with imperfections (a circular central delamination) subjected to blast loading is treating. The methodology for the blast pressure charging and the mechanism of the blast wave in free air are given. The space pressure variation is determined by using Friedlander exponential decay equation. Various scenarios (parametric calculus) to evaluate the behavior of the ship structure composite plate to blast loading are presented: explosive magnitude, distance from source of explosion, position of the delamination.*
Keywords: *blast loading, composite laminated plates, delaminations*

1. INTRODUCTION

Nowadays, in the marine and shipbuilding industry composites have an ever growing importance. The main reason for the fabrication of composite structures is to provide a composite with high bending stiffness with overall low density. These composites are a very good material for ship hull structures such as shells, decks and bulkheads, where structures must be lightweight and strong.
Due to 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. 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 behavior, have motivated various assumptions and approximations to simplify the models.
In United States government distributed the simple blast program ConWep. Users can input a charge size and standoff distance and receive pressure for that point in relation to time as output. It also allows users to receive pressure data after interaction with simple structures such as plates and shells ([1]).
An explosion within or around a ship hull can have catastrophic effects, damaging and destroying internal or external portions of the ship hull structure. Explosion damage to the ship structure depends on the type and layout of the structure, material used, range of the located explosive device, and the charge weight (equivalent TNT mass). If a structure is designed for a blast loading, its behavior will be better, having more mass, more damping and energy-absorbing capacity. In this case, certain bomb scenarios have to be done during design stage.
The response of elastic structures to time-dependent external excitations, such as sonic boom and blast loadings, is a subject of much interest in the design of marine vehicles [[2], [3]]. For the case of blast loadings, various analytical expressions have been proposed and discussed in [4].
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 [4].
Methods presented in [4] use experimental data from explosive tests to develop expressions for the blast overpressure as a function of time and distance from the blast, as well as charge weight and other important blast parameters. Very few papers make use of such a realistic blast load. Most of the literature available concerning

impulsively loaded plates considers a linear solution for isotropic plates. There are also many linear solutions available for impulsively loaded composite plates, and some of the references listed thus far are of this type ([5]). Recent work on polymer matrix fiber-reinforced composite has focused on the advantages of this type of construction under blast loads when the deformations remain dominantly elastic. The relative advantage of composite plates over solid plates has not been firmly established for metal construction when strong blast loads require both high strength and energy absorption ([6]).
Predicting the structural response to such an explosion requires accurate prediction of the applied pressures and a solution procedure that is adequate for such transient phenomena.
The work presented here focuses on the composite laminated plates with imperfections response to such close proximity explosions. In particular, the structures considered include orthotropic composite and contacting plates subject to mine blasts.

2. BLAST WAVE PROPAGATION IN AIR

In a blast analysis, one can find the size and location of the explosion to protect against. By using the relationship that the intensity of a blast decays in relation to the cube of the distance from the explosion one can adopt an idealized blast wave and at the target. The positive phase duration of the blast wave is compared with the natural period of response of the structure or analyzed element.
The response of the structural element can be defined by two possible extreme loadings: a) Impulsive loading, occurring in the case of load pulse is short compared to the natural period of structure vibration; b) quasi-static or pressure occurring in the case of long duration of the load, compared to the natural period of structure vibration. The case with a regime where the load duration and structural response times are similar, the loading is of dynamic or pressure time type ([7]).
The explosion is characterized by transient air pressure wave moving further from the source of explosion. The peak overpressure (the pressure above the normal atmospheric pressure) and duration of the overpressure vary with the distance from the centre of explosion. As the wave moves further from the source of explosion the peak overpressure drops. Stand-off distance is a fundamental parameter when determining the blast pressure experienced by a structure. Values of components such as high-mass, long span beams and floors can absorb a great part of the energy delivered by a blast load.

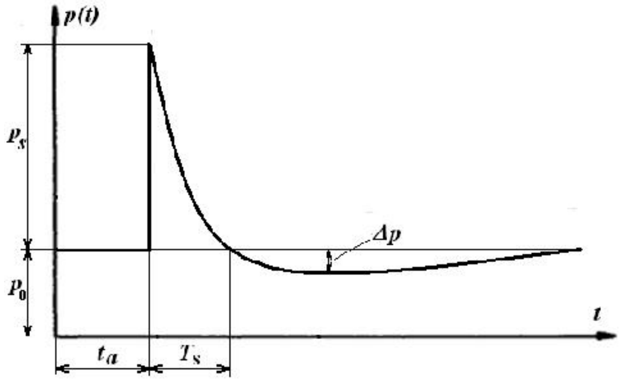

Figure 1: Typical blast pressure - time profile

The pressure at a specific point in air in the path of an explosion over time will follow the same general pattern, so long as does not exist any reflection from nearby objects.
This pattern, called an overpressure curve (Fig.1) has main components: the detonation, arrival time (t_a), peak pressure (p_s), and time duration (T_s). The detonation can be considered as time 0, while the arrival time is the time that it takes for the pressure wave to reach the point of interest. Once the peak pressure is reached, it immediately starts to decay to the normal pressure during the time duration. As the material in the blast wave expands outward it can leave a void, creating a region with pressure lower than normal atmospheric pressure. The size, shape and material of the charge, as well as the stand off distance determine the magnitude and shape of this curve. In addition to the above factors, the blast wave and the pressure involved can reflect off of surfaces in various directions, and cause further fluctuations in pressure at a single point.
For describing the pressure-time history of a blast wave, certain equations have been developed and used in the calculus. The most frequently used is the modified Friedlander equation, describing the pressure after its arrival

$$p(t) = p_0 + p_s\left(1 - \frac{t}{T_s}\right)e^{-\frac{bt}{T_s}} \tag{1}$$

In Eq. (1), p_s denotes the peak reflected pressure in excess of the ambient one; T_s denotes the positive phase duration of the pulse measured from the time of impact of the structure and b denotes a decay parameter which has to be adjusted to approximate the overpressure signature from the blast tests.
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 ps (in kPa) due to spherical blast based on scaled distance Z, were introduced in [8] as:
- for $p_s > 1000$ kPa

$p_s = 670 / Z^3 + 100$,

- for $10 < p_s < 1000$ kPa

$p_s = 97.5 / Z + 145.5 / Z^2 + 585 / Z^3 - 1.9$

where Z is the dimensional distance parameter (scaled distance)
$Z = R/W^{1/3}$
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.

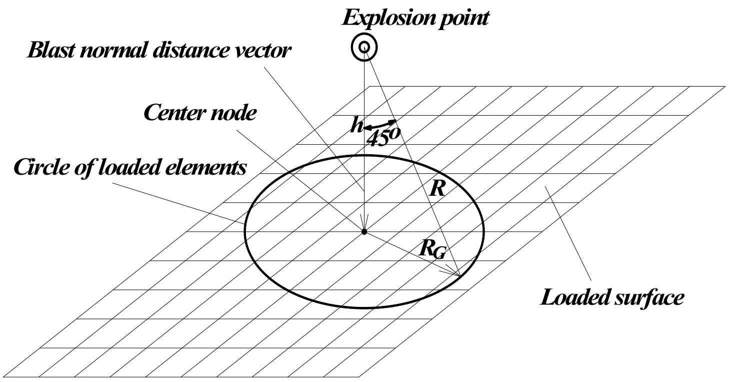

Figure 2: Blast pressure evaluation model

As it is shown in the figure 2, the methodology and model to determine the pressure from blast loading is presented. According to the actual effective distance from the explosion R (Fig. 2), elements within 45 degrees of the blast normal vector are divided into groups based upon their average distance to the center node. Only elements within the 45 degree cone are loaded. The area within the cone is divided into a number of 10 rings to determine the pressure acting on the elements of the mesh. The distribution of the blast load on the plate using 10 load rings is shown in the figure 3.

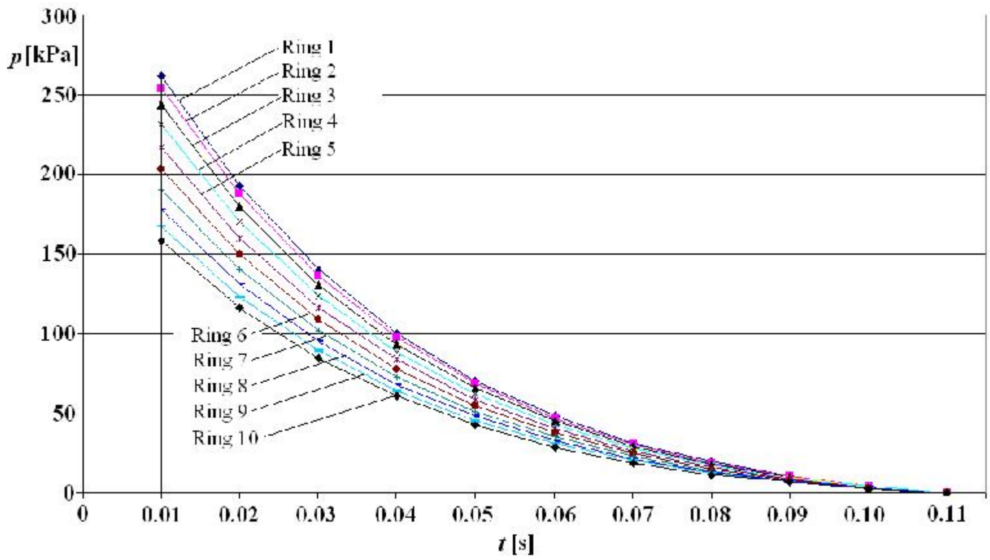

Figure 3: Pressure - time histories for all rings

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 has its own pressure-time history as it is shown in figure 3.

The time duration Ts is determined from a natural vibration calculus, being equal to natural period of response of the structure ([9]).

3. DELAMINATION MODEL

The finite element delamination analysis was carried out using COSMOS/M finite element software. There are several ways in which the panel can be modeled for the delamination analysis. For the present study, a 3-D model with 4-node SHELL4L composite element of COSMOS/M is used. The panel is divided into two sub-laminates by a hypothetical plane containing the delamination. For this reason, the present finite element model would be referred to as two sub-laminate model. The two sub-laminates are modeled separately using 4-node SHELL4L composite element, and then joined face to face with appropriate interfacial constraint conditions for the corresponding nodes on the sub-laminates, depending on whether the nodes lie in the delaminated or undelaminated region.

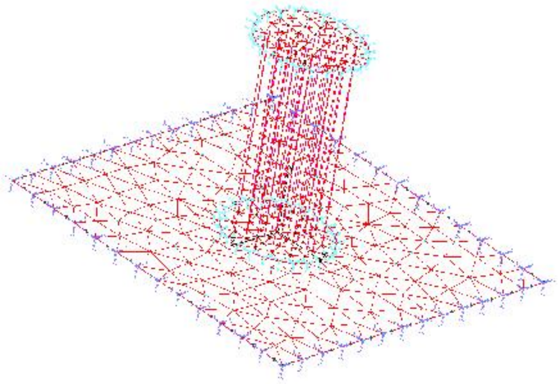

Figure 4: Delamination model

The delamination model has been developed by using the surface-to-surface contact option (Fig. 4). In case of surface-to-surface contact, the FE meshes of adjacent plies do no need to be identically. The contact algorithm of COSMOS/M has possibility to determine which node of the so-called master surface is in contact with a given node on the slave surface. Hence, the user can define the interaction between the two surfaces.

In the analysis, the certain layers are intentionally not connected to each other in ellipse regions. The condition is that the delaminated region does not grow. In COSMOS/M these regions were modeled by two layers of elements with coincident but separate nodes and section definitions to model offsets from the common reference plane. Thus their deformations are independent. At the boundary of the delamination zones the nodes of one row are connected to the corresponding nodes of the regular region by master slave node system.

In the calculus done in this paper, the delamination has a circular shape, with diameter of 50 mm, placed in the middle of the plate, between layers 1 and 2.

4. FEM ANALYSIS OF THE PLATE

The applied blast impulse is calculated using the plate mesh. The studies were carried out on a square plate from the ship side shell placed between two pairs of web stiffeners. So, the plate can be considered as being clamped on the all sides. The area of each of the ring zones is easily calculated from the formula for the cross sectional area of a cylinder. These individual areas are then multiplied by the corresponding impulse per unit area to obtain the total applied impulse. Using the ideal and applied impulse values, a percent error for the applied impulse can be determined.

The material is E-glass/polyester having the symmetric stack. The stack of the shell is according to the topologic code [A/B]3s.

The layers made of material A, have the thickness of 0.25 mm and characteristics:

E_x=80 GPa, E_y=80 GPa, G_{xy}=10 GPa, μ_{xy}=0.2

The layers made of material B, have the thickness of 0.1 mm and characteristics:

E_x=3.4GPa, E_y=3.4GPa, G_{xy}=1.3GPa, μ_{xy}=0.3.

Due to the double symmetry, one quarter of plate was studied.

In the non-linear calculus, Tsai-Wu criterion was considered for the limit state stresses evaluation.

Time variation of the maximum von Mises stress obtained in the point placed on the middle of the side plate are presented in figure 5 (material with damping characteristics) and figure 6 (material without damping characteristics). 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.

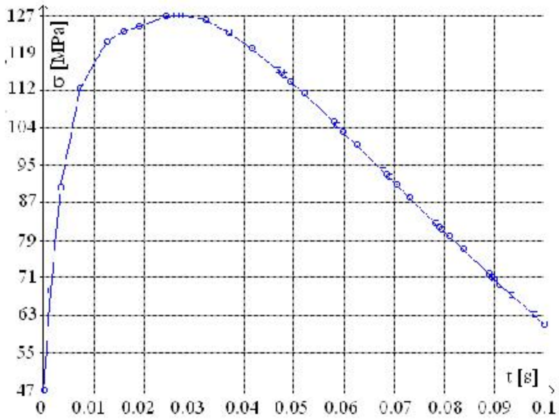

Figure 5: Maximum von Mises stress on the sides of the plate with damping

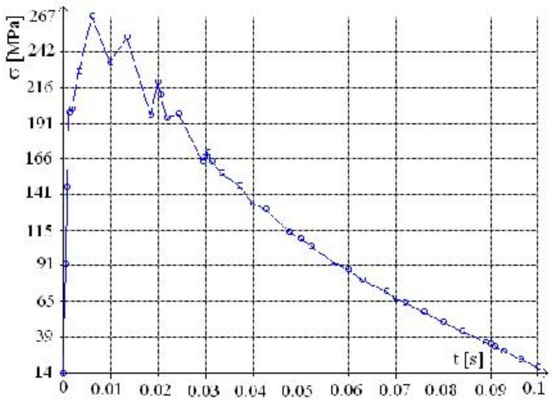

Figure 6: Maximum von Mises stress on the sides of the plate without damping

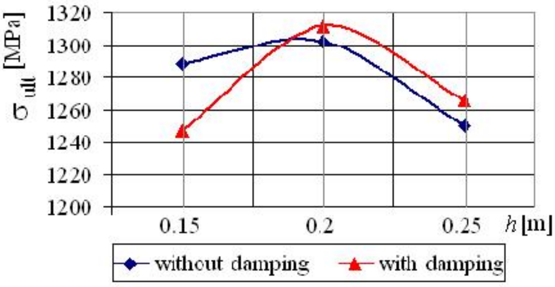

Figure7: The variation of ultimate stress (Fail 1 - tension) for *t*=2.1mm, in the case *W*=0.7kg

5. CONCLUSION

For high-risks facilities such as navy and commercial ships, design considerations against extreme events (bomb blast, high velocity impact) are very important. It is recommended that guidelines on abnormal load cases and provisions on progressive collapse prevention should be included in the current ship hull structure design norms. Requirements on ductility levels also help improve the structure performance under severe load conditions.
Dynamic calculus was done with COSMOS/M soft package using specific elements SHELL4L.
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 7 the variation of maximum stress versus equivalent TNT mass *W* for plate thickness of 2.1mm 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. 1). 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 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. In the case of W=0.7kg in all cases of distance h and thickness t the variations of failure criterion for tension (Fail 1) are presented in figure 7. As it is seen, generally speaking, the damping "is helping" the plate integrity: the stress when the Fail 1 (case of tension) is occurring in the case of damping is greater than the plate without damping.
According to the analysis, the developed blast simulation model and optimal design system can enable the prediction, design and prototyping of blast-protective 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 composite structure with special damping system can help the structure to sustain blast load. The inclusion of a damping material in the 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 plate material.

ACKNOWLEDGEMENT

The authors acknowledge the financial support received for this work from the Romanian UEFISCDI Project 168 EU (2012-2014).

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