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Underwater explosion response of curved composite plates

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ABSTRACT

The effect of plate curvature, plate thickness, and thickness distribution on the response of curved composite plates subjected to far field underwater explosion (UNDEX) loading has been studied through computational simulations. In this study five panels with increasing radii of curvature are considered. Furthermore, the effect of plate thickness is considered by investigating three plate thicknesses for a given radii of curvature. Finally, a comparison is made between a plate with a uniform thickness and a plate with equal mass but a thicker outer boundary and thinner midsection. The effects are assessed using the plate center point deflection, full field deformation evolution, and fluid structure wave interaction. The results show that when subjected to shock pressure loading the deformation mechanics of the plate is significantly affected by the amount of curvature, thickness, and thickness distribution.

1. Introduction

The use of composite materials is becoming increasingly prevalent in a wide variety of structural applications including ship hull designs, advanced airframes, and military ground vehicles. The advantages of composite materials include high specific strengths, greater design flexibility, improved corrosion resistance, and overall reduced maintenance costs. However, the use of these materials in a military environment requires that they be able to survive extreme loading conditions including ballistic and shock events. Utilization of these materials in naval applications subjects them to the specific risk of the exposure to underwater explosion (UNDEX) events. The response of composites under shock loading conditions has recently been investigated utilizing both experimental and computational methods. However the level of understanding of the response of these materials at these high loading rates is not as established as that under static conditions. When shock loading is a concern, this typically results in the conservative design of composite structures leading to overdesigns which do not afford the full weight advantage afforded by these advanced materials.

Composite materials subjected to highly transient loading conditions experience damage in the form of distinct mechanisms including fiber breakage, matrix cracking, and inter-laminar delamination. A large number of studies, both experimental and computational, have been performed on composite materials subjected to highly transient loading conditions in order to study these damage mechanisms and associated evolution. Studies on shock loading of composite materials have examined the material response over a range of loading rates. Tekalur et al. [1] investigated the effects of blast loading on both E-Glass and Carbon based laminates through the use of a small scale explosion tube to consider the shock load combined with the effects of the heat generated during combustion of the explosive materials. Mourtiz has studied the effect of shock loading on the flexural [2] and fatigue [3] properties of composite laminates when subjected to underwater shock loading. LeBlanc et al. studied the effects of shock loading on composites subjected to UNDEX loading through computational and experimental methods [4,5]. Work by Latourte et al. [6] utilized a scaled fluid structure method [7] to study the failure modes and damage mechanisms in both monolithic and sandwich plates subjected to underwater impulsive loads. Schiffer and Tagarielli [8] utilized a transparent shock tube coupled with high speed photography and numerical simulations to investigate the response of circular composite plates including plate deformation mechanisms and cavitation development. The effects of underwater explosion bubbles on the response of a stiffened composite hull structure has been studied by Gong and Khoo [9] through a combined boundary element and finite element method. Wei et al. [10] have developed a fluid–structure interaction model to study both monolithic and sandwich composite plates subjected to underwater blast loading and found that there is a strong strain rate sensitivity on the overall damage evolution of the panels, specifically delaminations. The use of three-dimensional fiber architectures to improve the shock response of composite

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laminates through the use of through thickness fibers has been investigated experimentally and numerically. Pankow et al. [11] utilized an air driven shock tube to study the effect of shock loading on 3D composites in terms of damage mechanisms and transient response. The results of the study indicate there is likely an optimal *Z*-direction fiber content to reduce damage and maximize panel stiffness. A corresponding computational study [12] was shown to accurately simulate the experimental results.

Due to the complexity of many advanced structural designs, curved plates are common. The complexity of these geometrical designs results in structural responses that are significantly different from flat panels, specifically when subjected to transient loading conditions such as shock. Kumar et al. investigated the effect of panel curvature on both aluminum [13] and carbon composite [14] panels through the use of air driven shock tube and found that as the radius of curvature is decreased (sharper curvature) the plate sustains localized central damage rather than overall plate flexure. Saghafi et al. [15] investigated the effect of preload on the impact response of singly curved composite panels and found that while there was an increase in damage with increasing preload, there was a decrease in overall energy absorption and plate deflections.

The objective of this study is to investigate the effect that plate curvature has on the deformation mechanics and fluid structure interaction of doubly curved composite panels subjected to underwater explosive loading conditions. This is accomplished by extending a previously developed finite element model, which was validated to test data, to account for varying levels of plate curvature and evaluating the plate response.

2. Composite material model

The composite material used in the simulations presented in this paper is an E-Glass/Vinyl ester composite with a 0–90° biaxial layup. The glass fabric is a balanced construction of 0° and 90° fibers with the two layers being stitched together rather than woven. This material was utilized in the experimental work [5] which serves as the foundation for the current study. The panels consist of 3 plys of the fabric, with each ply oriented in the same direction, i.e. the 0° fibers in each ply are parallel. The plates have a total thickness of 1.37 mm (0.054 in.) and a fiber content of 62% by weight. The material properties are listed in Table 1 and were previously determined through testing per ASTM specifications.

Table 1
E-Glass/Vinyl ester biaxial laminate – mechanical properties (ASTM 638).

	MPa (lb/in^2)
Tensile modulus (0°)	15.8e3 (2.3e6)
Tensile modulus (90°)	15.8e3 (2.3e6)
Tensile strength (0°)	324 (47,000)
Tensile strength (90°)	324 (47,000)

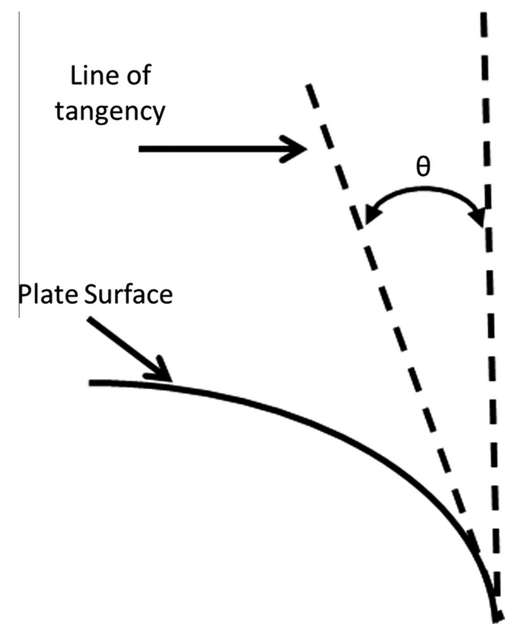

Fig. 1. Plate curvature measure defintion.

3. Panel configurations

3.1. Curvature configurations

This study examines the effect of plate curvature by varying the panel geometry from shallowly curved to a near hemisphere. The measure of curvature is taken to be the angle between the vertical axis and the line of tangency with respect to the vertical axis, Fig. 1. Using this measure, the shallowest plate curvature has an angle of tangency of 75° and the most highly curved plate has an angle of 15°. In the current investigation, 5 plate curvatures are chosen with angles of tangency ranging from 15° to 75° in 15° increments as shown in Fig. 2. In all cases the plates are oriented such that the shock pressure load acts on the convex face of the plate.

3.2. Thickness configuration

In addition to the plate curvatures discussed in the prior section, the effect of thickness on the shock response of curved composite panels has been investigated through 2 methods. In the first approach, the overall panel thickness was uniformly increased by 25% and 50% for an overall panel thickness of 1.71 mm and 2.05 mm respectively. This results in plates which are also 25% and 50% heavier as compared to the 1.37 mm baseline panel. The second approach utilizes a redistribution of material to the outer edge of the plates with a corresponding thickness decrease in the central region of the plate. This results in a plate which has an equivalent mass to the baseline plate, but with a thicker out ring of material. The thicker ring of material is indicated by the gray color in Fig. 3, with the reduced thickness central region indicated by blue.[1] This thicker region in the plate configuration is 1.83 mm (33% increase from baseline of 1.37 mm) and through the conservation of overall panel weight the central region is 1.02 mm. The goal of this panel configuration was to determine if the overall panel inversion process could be arrested by preventing the formation of a hinge at the boundary (see deformation mechanics discussion below). For each panel configuration, only the 45° curvature is evaluated to determine the meaningful trends.

4. Conical shock tube

The experimental results which act as the validation for the computational model were obtained through the use of a conical shock tube (CST) facility located at the Naval Undersea Warfare Center, Division Newport. Although the tube is not utilized in the current study, the UNDEX pressure loading from the experiments is used to drive the models and thus a brief overview is provided for background [Full details are found in [5]]. The shock tube is a horizontally mounted, water filled tube with a conical internal

[1] For interpretation of color in Fig. 3, the reader is referred to the web version of this article.