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The dynamic response of composite plates to underwater blast: Theoretical and numerical modelling

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ABSTRACT

Analytical models are developed to predict the response of circular, fully clamped, orthotropic elastic plates to loading by a planar, exponentially decaying shock wave in water. The models consider the propagation of flexural waves in the plates as well as fluid–structure interaction prior and subsequent to water cavitation. The analytical predictions are compared to those of detailed dynamic FE simulations and the two are found in good agreement. It is shown that an impulsive description of the loading can lead to large errors. A comparison of the responses of cross-ply and quasi-isotropic laminates shows that the composite layup has a minor influence on the underwater blast performance. Design charts are constructed and used to determine plate designs which maximise the resistance to underwater blast for a given mass.

1. Introduction

While composite materials are progressively adopted in naval constructions and in the off-shore industry, their resistance to underwater blast is gaining great relevance. Underwater explosions give rise to spherical shock waves, travelling in water at approximately sonic speed [1]. At sufficient distance from the detonation point, such waves can be considered as planar. The structural response ensuing from blast wave impact is, in general, governed by the propagation of elastic and plastic waves and thus can be considerably different to that caused by static loading.

Studies on the dynamic response of ductile structures date back to World War II. Early theoretical work on the transient response of thin plates subject to transverse dynamic loads was carried out by Hudson [2] and Wang and Hopkins [3] who established theoretical models for the dynamic plastic response of thin metallic plates subject to impulsive loads. A comprehensive account of the dynamic behaviour of beams, plates and shells made from idealised rigid-perfectly plastic materials is given in Jones [4].

Composites are anisotropic elastic solids and exhibit, when subjected to transverse impulsive loads, a response which results in a full spectrum of elastic waves propagating in radial direction [5]. Experimental observations of such flexural wave propagation phenomena in elastic solids are reported in the literature [6,7]. The application of a dynamic pressure history on the surface of a composite also initiates propagation of compressive through-thickness stress waves [8], however these do not affect substantially the response of slender elastic plates.

A considerable body of literature exists on the transient response of isotropic and orthotropic elastic plates subject to various type of dynamic loads. The usual analytical treatment follows that given in Zener [9] who expressed the transient response of thin simply-supported isotropic plates in terms of mode shapes and natural frequencies that automatically satisfy the boundary conditions, and used it to analyse the impact of spheres on large plates. A similar approach was used by Olsson [10] who extended the theory of Zener [9] to the case of orthotropic plates. Sun and Chattopadyay [11] employed a similar technique to investigate the central impact of a mass on a simply-supported laminated composite plate under initial stress, by employing a plate theory that accounts for transverse shear deformations [12]. They also noted that rotary inertia has minor effect in the dynamic response and can therefore be neglected. Dobyns [13] used the same plate theory [12] to analyse the dynamic response of composite plates to loading by pressure pulses of various shape, in order to mimic different types of blast loading. Most of these investigations obtained small-strain bending solutions which neglected the presence of stretching

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forces and shear deformation in the plates, which is reasonable for simply-supported structures.

Solutions for the dynamic response of plates with fully clamped boundaries, where stretching forces cannot be neglected, are obtained in the published literature via approximate techniques such as the Rayleigh–Ritz method, due to the fact that closed-form solutions are not available in this case. The Rayleigh–Ritz method was employed by Quian & Swanson [14] for the impact response of rectangular carbon/epoxy plates. A simplified method for solving the wave propagation problem in elastic structures is presented in Hoo Fatt and Palla [15] for the case of composite sandwich plates subject to loading by a prescribed pressure history.

Blast loading of submerged structures results not only in dynamic deformation but also in complex cavitation phenomena in the surrounding water. Such fluid-structure interaction (FSI) phenomena significantly affect the structural response and need to be thoroughly understood when designing naval constructions against underwater blast. Pioneering work on FSI dates back to the early 1940s; Taylor [16] investigated the response of a rigid free-standing plate loaded by an exponentially decaying, planar shock wave and concluded that the momentum transmitted to the plate in a blast event can be dramatically reduced by decreasing the plate's mass, with the reductions in momentum a consequence of early cavitation at the fluid-structure interface. Kennard [17] theoretically studied transient cavitation in elastic liquids and found that, when the pressure drops below the cavitation limit at a point in the fluid, two 'breaking fronts' emerge from this point and propagate in opposite directions, creating an expanding pool of cavitated liquid. Subsequently, such breaking fronts can arrest, invert their direction of motion and become 'closing fronts', forcing contraction of the cavitation zone.

An extensive part of the recent blast loading literature focused on the benefit of replacing monolithic structures with sandwich panels of equivalent mass. Several theoretical and numerical studies [18-23] have shown that sandwich panels can outperform monolithic plates of equal mass in terms of the impulse delivered to the structure in a blast event. Similar results were obtained experimentally by other authors [7,24–27].

An analytical model for the response to underwater blast loading of clamped metallic sandwich beams is presented in Fleck and Deshpande [28] who mimicked underwater blast loading by assuming impulsive loading of the sandwich's front face sheet, with the impulse deduced from Taylor's theory [16]. Subsequently, Qiu et al. [22] extended these models to examine the impulsive shock response of clamped circular metallic sandwich plates (treated as rigid-perfectly plastic). Calculations based on Taylor's analysis are only applicable for a limited range of problem geometries and loading characteristics and can lead to large inaccuracies outside these limits.

Recent theoretical work by Schiffer et al. [29] examined the effects of an initial hydrostatic pressure on the 1D response to underwater blast loading of a rigid plate supported by a linear spring. These models capture propagation of breaking fronts and closing fronts [17] as well as their interactions with the structure in a blast event; their predictions allowed concluding that both the cavitation process and the structural response are extremely sensitive to the initially applied pressure, consistent with the findings of companion studies [30,31].

Although considerable effort has been devoted to understanding the effects of FSI on the 1D response of monolithic plates [16,29] and sandwich panels [18,19,21,31] it still remains unclear how these phenomena affect the response of realistic structures such as plates, beams or shells, in which both dynamic deformation and FSI are 2D or 3D in nature.

In this study we shall answer this question by constructing an approximate analytical model for the dynamic response produced by underwater blast loading of clamped circular elastic plates. The developed theory takes into account effects of transverse shear deformations, stretching forces due to large deflections, the orthotropic material response of fibre-reinforced laminated composites as well as flexural wave propagation phenomena. Fluid–structure interaction phenomena prior and subsequent to first cavitation will be taken into account in this study.

The outline of this paper is as follows: in Sections 2 and 3 we derive the analytical models and describe the FE scheme employed; in Section 4 we present a comparison between analytical and FE predictions and construct a non-dimensional design map in order to determine the optimal plate geometries which maximise the resistance to underwater blast; finally, we summarise the main conclusions of this study in Section 5.

2. Analytical models

2.1. Simplifications in the treatment of elastic waves

Experimental observations [7] have shown that underwater blast loading of circular composite plates by planar shock-waves gives rise to the propagation of flexural waves, emanating from the plate boundary and propagating towards the plate centre, as

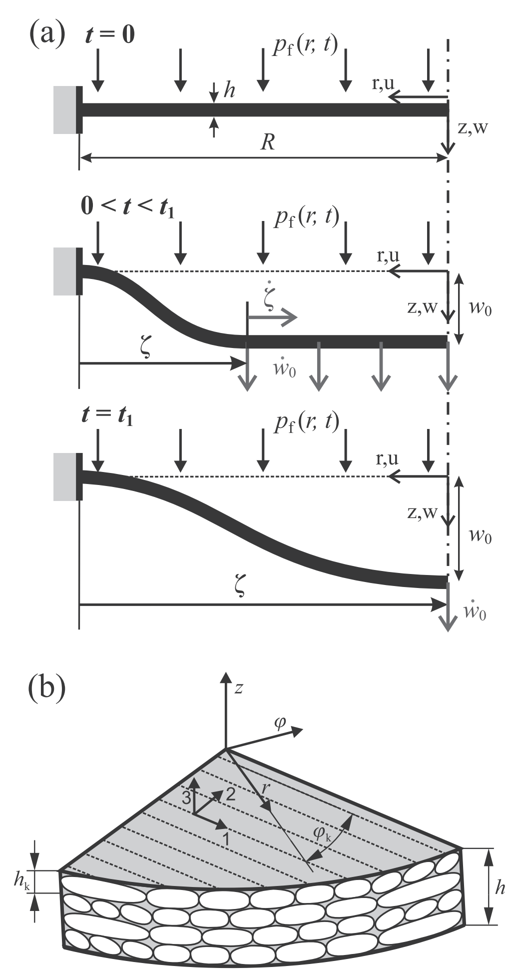

Fig. 1. (a) Assumed dynamic plate deformation consequent to pressure loading, showing initial configuration ($t = 0$), propagation of a flexural wave at velocity $\dot{\zeta}$ ($0 < t < t_1$), and arrival of the flexural wave at the plate centre ($t = t_1$); (b) section through a laminated composite plate showing material coordinates of the top lamina (1,2,3), lamina thickness h_k as well as global reference system (r,φ,z) and thickness h of the laminate.