Journal of the Mechanics and Physics of Solids 59 (2011) 1623–1646

Contents lists available at ScienceDirect

Journal of the Mechanics and Physics of Solids

journal homepage: www.elsevier.com/locate/jmps

Failure mechanisms in composite panels subjected to underwater impulsive loads

Félix Latourte [a,1,2], David Grégoire [a,1,3], Dan Zenkert [b], Xiaoding Wei [a], Horacio D. Espinosa [a,*]

[a] Northwestern University, 2145 Sheridan Rd., Evanston, IL 60208-3111, USA
[b] KTH-Royal Institute of Technology, Sweden

A R T I C L E I N F O

Article history:
Received 28 August 2010
Received in revised form
19 March 2011
Accepted 15 April 2011
Available online 21 April 2011

Keywords:
Composite materials
Fluid–structure interaction
Dynamic failure
Delamination
Blast

A B S T R A C T

This work examines the performance of composite panels when subjected to underwater impulsive loads. The scaled fluid–structure experimental methodology developed by Espinosa and co-workers was employed. Failure modes, damage mechanisms and their distributions were identified and quantified for composite monolithic and sandwich panels subjected to typical blast loadings. The temporal evolutions of panel deflection and center deflection histories were obtained from shadow Moiré fringes acquired in real time by means of high speed photography. A linear relationship of zero intercept between peak center deflections versus applied impulse per areal mass was obtained for composite monolithic panels. For composite sandwich panels, the relationship between maximum center deflection versus applied impulse per areal mass was found to be approximately bilinear but with a higher slope. Performance improvement of sandwich versus monolithic composite panels was, therefore, established specially at sufficiently high impulses per areal mass ($I_0/\bar{M} > 170\ \mathrm{m\,s^{-1}}$). Severe failure was observed in solid panels subjected to impulses per areal mass larger than $300\ \mathrm{m\,s^{-1}}$. Extensive fiber fracture occurred in the center of the panels, where cracks formed a cross pattern through the plate thickness and delamination was very extensive on the sample edges due to bending effects. Similar levels of damage were observed in sandwich panels but at much higher impulses per areal mass. The experimental work reported in this paper encompasses not only characterization of the dynamic performance of monolithic and sandwich panels but also post-mortem characterization by means of both non-destructive and microscopy techniques. The spatial distribution of delamination and matrix cracking were quantified, as a function of applied impulse, in both monolithic and sandwich panels. The extent of core crushing was also quantified in the case of sandwich panels. The quantified variables represent ideal metrics against which model predictive capabilities can be assessed.

1. Introduction

Glass reinforced plastic (GRP) composite materials are of current interest in naval hull construction (Mouritz et al., 2001), because they exhibit low weight and low magnetic signature. These are advantages of particular interest to naval

* Corresponding author.
E-mail address: espinosa@northwestern.edu (H.D. Espinosa).
[1] These authors contributed equally.
[2] Current affiliation: EDF–R&D, MMC, Avenue des Renardières, 77818 Moret-sur-Loing, France.
[3] Current affiliation: LFC-R, UMR5150, Université de Pau et des Pays de l'Adour, Allée du Parc Montaury, 64600 Anglet, France.

0022-5096/$ - see front matter
doi:10.1016/j.jmps.2011.04.013

designers interested in fast and stealth marine structures. Two different architectures are generally used to build composite hulls: single-skin design and sandwich construction, where a crushable core is encased between fiber-reinforced face skins. Both architectures involve the use of frames, stiffeners and bulkheads that provide the overall structural stiffness, and support the GRP monocoque or sandwich hull. In these constructions, the connection between the hull and the bulkhead does not seem to be a weak point when subjected to blast loading. Indeed, no localized shear or tearing was observed in full scale blast experiments (Hall, 1989). These experiments showed that deformation and damage are distributed on the sandwich panel itself, in which interlaminar delamination occurs. A visible change in opaqueness in the hull skin appeared after the impulsive loading (Hall, 1989).

Large scale field blast experiments have also been conducted. In these experiments, a 3D digital image correlation technique was employed to reconstruct the deformation histories of the tested panels (Dear et al., 2009). At the laboratory scale, experimental studies were conducted to study the dynamic response of composite sandwich beams subjected to projectile impact (Tagarielli et al., 2007; Johnson et al., 2009), the ballistic resistance of 2D and 3D woven sandwich composites (Grogan et al., 2007) and the impact response of sandwich panels (Schubel et al., 2005; Tekalur et al., 2008) with optimized nanophased cores (Bhuiyan et al., 2009; Hosur et al., 2008). The reader interested in the numerous experimental studies of marine composite subjected to impulsive loadings can refer to Porfiri and Gupta (2009). These studies present the performance of different composite panels and the most significant damage modes involved in blast or ballistic resistance of sandwich structures, whose local degradation can greatly affect the overall structural performance (Zenkert et al., 2005). One limitation of the experiments reported in the literature is that the impacted region is typically small compared to the panel or laminate dimension, resulting in very localized damage. Localized damage is also not representative of the structural effects observed in larger scale blast studies, where clamping tearing is not the most significant mechanism responsible for structural failure, and deformation and damage are spread over a large section of the hull.

Scaled down laboratory fluid–structure interaction experiments have been successfully developed and applied to the investigation of monolithic steel plates (Espinosa et al., 2006; Rajendran and Narashimhan, 2001) and sandwich steel constructions (Mori et al., 2007, 2009) by Espinosa and co-workers. In the present paper, the fluid–structure interaction (FSI) setup introduced in Espinosa et al. (2006) is utilized to characterize composite monolithic and sandwich plates. The advantage of this setup relies on the scaling of full field loads that enable the testing of panels with dimensions (radius $L=76.2$ mm) small enough to be easily manufactured and handled in a laboratory setting, but with sufficient thickness to investigate layups consistent with full marine hulls in terms of stacking sequence and number of plies. Moreover, the setup is highly instrumented and allows recording of deflection profile histories over the entire span of the panels for a precisely known applied impulse.

Composite panels subjected to blast typically present not only extensive interlaminar fracture (delamination) but also matrix microcracking and ultimately fiber fracture at the highest impulses. In sandwich panels, these failure modes are affected by interactions between the core and the facesheets. Therefore, substantial improvements in the panel performance rely on the core crushing behavior and the strength of the core-facesheet bond. As a general trend, soft cores are generally preferred since they can enhance energy absorption and blast mitigation, which is key in panel performance. Foam crushing is typically characterized by a stress plateau followed by densification and sudden increase in hardening. Among core materials, PVC foam and balsa wood cores were investigated because of their suitable crushing strength in naval applications. Unfortunately, very limited experimental data exists concerning the performance and failure of composite panels subjected to impulsive loading (Tagarielli et al., 2007; LeBlanc and Shukla, 2010). Therefore, understanding and quantifying failure modes in composite materials, as a function of applied impulse, is a topic of research that requires additional attention from the community.

Concerning the prediction of structural behavior and failure of monolithic and sandwich hulls subjected to impulsive loadings, limited work was reported in the literature (Deshpande and Fleck, 2005; Hoo Fatt and Palla, 2009; Tilbrook et al., 2009; Forghani and Vaziri, 2009). Although physically based, most models rely on homogeneous description of the composite material at the scale of the single ply or of the sub-laminate (Hashin, 1980; Hashin and Rotem, 1973; Puck and Schurmann, 1998). A research initiative called *world-wide failure exercise* attempted to rank and classify the numerous models available in the literature based on their performance to predict failure under various loading conditions (Hinton et al., 2002; Soden et al., 1998; Soden et al., 2002; Soden et al., 2004). Surprisingly, investigated models are unable to predict failure correctly over a wide range of quasi-static stress paths. Therefore, attempts to establish predictive capabilities for composite materials have to be considered with care. Detailed experimental validation needs first to be attempted, especially in dynamic situations for which the literature is scarce. In this context, recently introduced multiscale models (Ladeveze and Lubineau, 2002; Ladeveze et al., 2006; Espinosa et al., 2000; Latourte et al., 2009; Espinosa et al., 2009) accounting for microstructural damage mechanisms developed in the framework of Hashin's damage mechanics (Hashin, 1986) might be of significant benefit to the composite modeling community.

The objective of the present paper is to characterize composite panel performance in terms of impulse-deflection, using the experimental methodology introduced in Espinosa et al. (2006). Failure modes, damage mechanisms and their spatial distributions are identified and quantified for composite monolithic and sandwich panels subjected to underwater impulsive loading. The quantified variables represent ideal metrics against which model predictive capabilities can be assessed. The paper is structured as follows: first, the tested composite panels are described and details about the manufacturing are given. Then, the experimental results are presented. These latter sections recap briefly the