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Estimation of transverse shear force during slamming impacts on a simply supported composite panel using a strain derivative method

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ABSTRACT

Use of sandwich constructions in slamming regions of high speed marine craft has led to increased consideration of the applied transverse shear force. Low shear strength core materials can lead to transverse shear failure becoming a high risk failure mode. Direct measurement of transverse shear force is difficult without altering the structure of the hull panels. This work utilises a non-invasive strain derivative method to estimate the applied transverse shear force. The basis of this method is the correlation between applied bending moment, determined from surface mounted strain gauges, and transverse shear force. A simply supported 1000 × 500 mm instrumented sandwich panel has been tested in the Servo-hydraulic Slam Testing System. Impacts have been undertaken at 10° with vertical velocities from 1.0 to 3.5 m/s. The shear force to bending moment ratio has been compared with the ratio based on a uniformly distributed load, as frequently used in design. An increase of up to 68% for the slamming experiments is observed. This significant difference illustrates a greater applied transverse shear force in slamming regions than would be predicted through the application of a uniformly distributed load.

1. Introduction

Pressures generated during slamming events are one of the most significant load cases for high speed craft. These pressures are generated during the dynamic impact of the hull of a vessel into the free surface of the water. Designers need an efficient process for establishing the required stiffness and strength of a hull structure. This is typically approached either by applying the guidelines as defined by class authorities or by utilising an in-house design methodology. In the majority of cases determining an appropriate slamming pressure load involves equating the anticipated non-uniform dynamic pressure to a uniform static pressure. For example the formula for calculating the magnitude of the equivalent uniform pressure for high speed light craft given by Det Norske Veritas is shown in Eq. (1) [1]. Of note is the fact that the water impact velocity is not considered, rather the design vertical acceleration of the longitudinal centre of gravity.

$$P_{DNV} = 1.3k_1 \left(\frac{\Delta}{nA}\right)^{0.3} T_0^{0.7} \frac{50-\beta_x}{50-\beta_{cg}} a_{cg} \tag{1}$$

It is difficult to compare a single impact with the specifications given by class authorities due to this use of acceleration rather than impact velocity in the calculations. Furthermore most scantlings from class authorities must be assessed in their entirety, rather than selecting a single parameter to compare, such as the slamming pressure.

Another option for comparison with results from single experimental impacts is predictions based on theoretical pressures. Established solutions for wedge impacts such as those based on the work of Wagner [2] or von Karman [3], given in Eqs. (2) and (3), can be used. In these solutions the average pressure increases with increasing impact velocity and decreasing deadrise angle.

$$P_{W,ave} = \frac{\rho\pi^2 v^2}{4\tan\beta\cos\beta} \tag{2}$$

$$P_{vK,ave} = \frac{\rho\pi v^2}{2\tan\beta\cos\beta} \tag{3}$$

Experimental values for transverse shear force and bending moment can be used to evaluate the ability of uniform pressure design methodologies, such as those specified by class authorities to predict shear and bending loads during slamming impacts.

Direct measurement of the transverse shear force is difficult experimentally, especially dynamically. Previously researchers have used invasive methods such as shear strain plugs [4] and

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Nomenclature

D	flexural rigidity [Nm]
M	bending moment [Nm]
T	shear force [N]
ε	strain [m/m]
z	distance to strain gauge from neutral axis [m]
d	distance between the neutral axes of sandwich skins [m]
Δx	distance between centre of two strain gauges [m]
q	uniform Pressure Magnitude [kPa]
a	panel width [m]
b	panel length [m]
β	deadrise angle [°]
v	vertical velocity [m/s]
ρ	density [kg/m^3]
Δ	displacement-tonnes
k_1	longitudinal distribution factor
n	number of hulls
L	vessel length [m]
T_0	draught at L/2 [m]
β_x	deadrise of transverse section [°]
β_{cg}	deadrise of centre of gravity [°]
α_{cg}	design vertical acceleration of centre of gravity [°]

shear rods [5]. These both require drilling holes into the core material which may lead to stress concentrations and unexpected variations in structural performance. For this work a non-invasive strain derivative method for determining the transverse shear force has been used. It is a development of the method by Cunningham [6]. Cunningham's work focused on the output from two gauges, while the method used here considers the strain from a series of gauges. The work here also builds on the previous work by the authors in this area [7,8].

A 1030 × 600 mm test specimen, with aluminium skins and an aramid honeycomb core, was manufactured for testing in a custom built Servo-hydraulic Slam Testing System for testing under water impact conditions. In addition to the panel, a beam specimen was manufactured measuring 600 mm long × 60 mm wide for experimentally obtaining the flexural stiffness and validating the strain derivative method.

The purpose of using aluminium rather than composite skins was to reduce the variability in strain measurement by using a homogeneous skin material. Previous attempts to use a strain derivative method on composite skins during slamming impacts in the SSTS were not successful due to scatter in the strain data when only considering a single pair of gauges [8]. The reason behind this was determined to be the micro-scale variations in the material properties of the composite skins leading to local spatial variations in the strain measurements. One option to improve the method would be to use strain gauges with a longer and/or wider sensor area. An increase in length however would reduce the accuracy of the method by increasing the averaging effect of each gauge. The other option, which was chosen, was to select a material without significant micro-scale variations in properties in order to develop and validate the method.

Hydroelasticity has been shown to vary the pressure distribution during slamming of flexible panels [9]. This variation will lead to a change in the transverse shear and bending moment distributions along the panel, therefore deformation should be kept to a minimum in this work to prevent significant variations with increasing impact velocity. A maximum deflection of 1.5% of span was selected for the testing. Stenius et al. [10] concluded that below 2% hydroelasticity was insignificant. Restricting deflection to below 1.5% will also ensure the deformations do not become significantly non-linear and membrane stress are negligible for a simply supported panel.

2. Test specimens

Details of test specimens are outlined in Table 1. In preparing the specimens the aluminium skins were bonded to the core using SA 70 epoxy adhesive film. The skins, adhesive film and core were stacked in order and placed under vacuum on a flat mould. The adhesive was then cured in an oven following the prescribed cycle time of a 40 min ramp to 82 °C, held at 82 °C for 3 h then cooled to 20 °C over 60 min.

The panel and beam were instrumented with strain gauges at the positions shown in Figs. 1 and 2 respectively. The specifications of the gauges are given in Table 2. All the gauges were aligned across the short span of the panel and along the length of the beam. The gauges located at location B on the beam and S5 on the panel are a single gauge with a linear array of sensors. These gauges (EA-06-031MF-120) come in a pre-fabricated array of 10. For the purposes of identifying the gauges at S5, they have been denoted C1–C10 in this work. C10 being closest to the outer edge of the panel. At location C a gauge is adhered to both the upper and lower surface of the beam in order to check the location of the neutral axis and that the strain is not affected by the boundary conditions. This also gives a measure of the symmetry of loading when compared with the strains at location B.

3. Experimental bending moment

Different load distributions will result in differing distributions of bending moment in the structure. A uniform pressure based slamming design load will give a distribution of bending moment symmetrical about the panel centre with the maximum bending moment at the centre of the panel for simply supported boundary conditions. Understanding the bending moment distribution and maximum bending moment in slamming impacts is important for optimising materials specifications and preventing structural failure.

The bending moment, M_x, can be determined from the measured strains using Eq. (4) [11]. This is only applicable for small deformations and no in-plane loads, which is the case for a simply supported plate with small deflections.

$$M_x = \frac{D}{1 - \nu_{xy}\nu_{yx}}\left[\frac{\partial^2 w_b}{\partial x^2} + \nu_{yx}\frac{\partial^2 w_b}{\partial y^2}\right] \tag{4}$$

Table 1
Details of panel and beam specimens.

Skin material	Al 5052 H34
Core material	HRH-10-3/8-3.0
Skin thickness	0.9 mm
Core thickness	18 mm
Flexural rigidity	11,250 Nm
Shear stiffness	1670 kN/m
Mass	8.0 kg/m^2