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The dynamic response of end-clamped sandwich beams with a Y-frame or corrugated core

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Abstract

The dynamic response of end-clamped monolithic beams and sandwich beams has been measured by loading the beams at mid-span using metal foam projectiles. The AISI 304 stainless-steel sandwich beams comprise two identical face sheets and either prismatic Y-frame or corrugated cores. The resistance to shock loading is quantified by the permanent transverse deflection at mid-span of the beams as a function of projectile momentum. The prismatic cores are aligned either longitudinally along the beam length or transversely. It is found that the sandwich beams with a longitudinal core orientation have a higher shock resistance than the monolithic beams of equal mass. In contrast, the performance of the sandwich beams with a transverse core orientation is very similar to that of the monolithic beams. Three-dimensional finite element (FE) simulations are in good agreement with the measured responses. The FE calculations indicate that strain concentrations in the sandwich beams occur at joints within the cores and between the core and face sheets; the level of maximum strain is similar for the Y-frame and corrugated core beams for a given value of projectile momentum. The experimental and FE results taken together reveal that Y-frame and corrugated core sandwich beams of equal mass have similar dynamic performances in terms of rear-face deflection, degree of core compression and level of strain within the beam.

Keywords: Sandwich beams; Dynamic response; FE simulations; Lattice materials

1. Introduction

Clamped sandwich beams are representative of sub-structures used in land-based and sea-based vehicles. These commercial and military vehicles are potentially subjected to dynamic loading above the quasi-static collapse strength. The response of monolithic beams and plates to shock-type loading has been extensively investigated. For example, Wang and Hopkins [1] and Symonds [2] have analysed the impulsive response of clamped circular plates and beams, respectively. However, their analyses were restricted to small deflections and linear bending kinematics. By direct application of the principle of virtual work for an assumed deformation mode, Jones [3] presented an approximate solution for simply supported circular monolithic plates undergoing finite deflections. Recently, Fleck and Deshpande [4] proposed an analytical model for the response of clamped sandwich beams to shock loadings including the effects of fluid–structure interaction: these analytical predictions are in close agreement with the finite element (FE) calculations of Xue and Hutchinson [5].

Over the past decade there have been substantial changes in ship design, see for example the review by Paik [6]. In the current study, we measure and analyse the dynamic performance of sandwich beams with a Y-frame sandwich core, as proposed by Schelde Shipbuilding[1] and as sketched in Fig. 1a. Full-scale ship collision trials reveal that the Y-frame design is more resistant to tearing than conventional monolithic designs, see Wevers and Vredeveldt [7] and Ludolphy [8]. Likewise, the FE simulations by Konter [9] suggest that the Y-frame confers improved perforation resistance. Naar et al. [10] have argued in broad terms that the ability of the bending-governed Y-frame topology to spread the impact load over a wide area, combined with the

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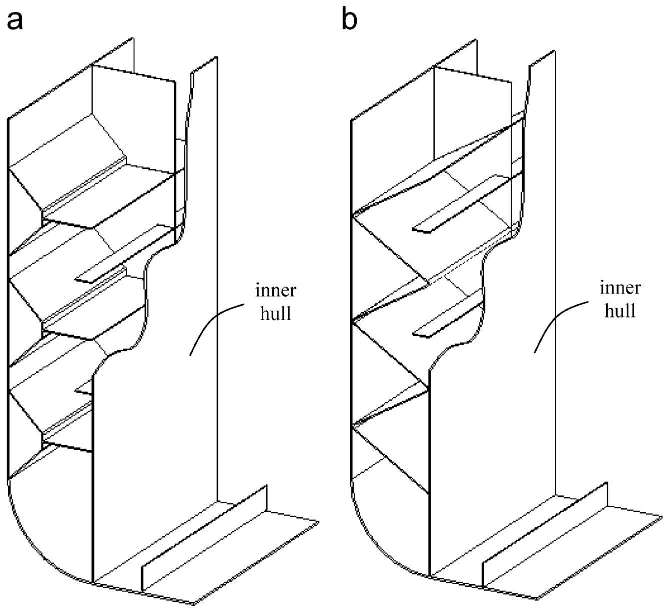

Fig. 1. Sketch of the (a) Y-frame and (b) corrugated sandwich cores as used in ship hull construction. The core is sandwiched between the inner and outer hulls of the ship.

in-plane high stretching resistance of the Y-frame, gives the enhanced performance of the Y-frame sandwich construction over conventional single and double hull designs. Similar to the Y-frame, the folded plate or corrugated sandwich core (Fig. 1b) has a prismatic topology and is considered as an alternative to the Y-frame design. The main aim of this study is to contrast the dynamic performances of sandwich beams with Y-frame and corrugated cores.

Pedersen et al. [11] and Rubino et al. [12,13] have investigated the *quasi-static* properties of Y-frame sandwich core structures while Côté et al. [14] studied the quasi-static response of the corrugated sandwich core. These studies reveal that the perfect corrugated core, absent geometrical imperfections and subjected to uniform macroscopic loading, is significantly stronger than the Y-core: the corrugated core deforms by plastic stretching of its struts, while the Y-core deforms by plastic bending. Geometrical imperfections and/or non-uniform loading (such as indentation loading) induce bending within the struts of the corrugated core and reduce its strength to approximately that of the Y-core.

Tilbrook et al. [15] have recently conducted a combined experimental and numerical investigation of the dynamic compressive response of the Y-frame and corrugated cores. They noted that the dynamic responses of the cores were dictated by (i) inertial stabilisation of the webs against buckling and (ii) plastic shock wave effects. Inertial stabilisation of the webs against buckling is the dominant dynamic strengthening mechanism at low velocities. At higher impact velocities, a plastic shock elevates the front face stresses above the level of rear face stress. To date, there have been little (or no) experimental data published on the dynamic response of Y-frame and corrugated sandwich core sandwich beams.

Only limited experimental data exist for blast loaded plates, with critical studies performed by Nurick and co-workers [16,17] who investigated the spatially uniform and localised blast response of square monolithic plates. By contrast, Radford et al. [18] have developed an experimental technique to subject structures to high-intensity pressure pulses using metal foam projectiles. The applied pressure versus time pulse mimics shock loading in air and in water, with peak pressures on the order of 100 MPa and loading times of approximately 100 μs. This laboratory method has been employed by Radford et al. [19] and Rathbun et al. [20] to investigate the dynamic response of clamped sandwich beams with metal foam and lattice cores. In the current study, we shall employ this experimental technique to explore the shock resistance of clamped sandwich beams with Y-frame and corrugated sandwich cores. The outline of the paper is as follows. First, the manufacturing route of the sandwich beams is detailed and the experimental protocol is described for loading the beams at mid-span by metal foam projectiles. The experimental results are discussed for two orientations of the core in the sandwich beams and for monolithic beams, and are then compared with FE predictions.

2. Experimental investigation

Metal foam projectiles were used to load dynamically clamped sandwich beams. The beams were made from AISI 304 stainless steel, and comprised two identical face sheets and either a Y-frame core or a corrugated core. The loading arrangement is sketched in Fig. 2a for the case of the Y-frame sandwich beam. The primary objectives of the experimental investigation are

(i) To compare the dynamic resistance of the sandwich beams with monolithic beams of equal areal mass, and made from the same material.
(ii) To contrast the dynamic strengths of sandwich beams made from a corrugated core and a Y-frame core.
(iii) To determine the accuracy of three-dimensional FE calculations in predicting the dynamic response and the onset of failure in the sandwich beams.

2.1. Specimen configuration and manufacture

The face sheets and core of the sandwich beams were manufactured from AISI type 304 stainless-steel sheet of thickness 0.3 mm and density $\rho_f = 7900\,\mathrm{kg\,m^{-3}}$. Both the Y-frame and corrugated cores were manufactured with an effective density $\rho_c \approx 200\,\mathrm{kg\,m^{-3}}$ and core depth $c = 22\,\mathrm{mm}$. Consequently, the effective relative density of the cores is $\bar{\rho} = 2.5\%$. All sandwich beams had an areal mass of magnitude $m = 2t\rho_f + c\rho_c \approx 10\,\mathrm{kg\,m^{-2}}$.

In order to define the core orientation, we introduce a local coordinate system (x_1, x_2, x_3) for the core, and a