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Dynamic response of metallic trapezoidal corrugated-core sandwich panels subjected to air blast loading – An experimental study

Pan Zhang [a], Jun Liu [a], Yuansheng Cheng [a,*], Hailiang Hou [b], Chunming Wang [c], Yong Li [a]

[a] School of Naval Architecture and Ocean Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[b] Department of Naval Architecture Engineering, Naval University of Engineering, Wuhan 430033, China
[c] School of Materials Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China

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ABSTRACT

The dynamic response of metallic trapezoidal corrugated core sandwich panels under air blast loading is studied by experimental investigation. The sandwich panels composed of two thin face skins and trapezoidal corrugated core, were designed and fabricated through folding and laser welding technology. The influences of the stand-off distance, face sheet thickness, core web thickness, core height and corrugation angle on the deformation/failure mechanisms and the permanent deflections of the trapezoidal corrugated core sandwich panels were investigated. Results revealed that the deflection and damage level of panel increased with the decrease of stand-off distance. The effect of front face sheet thickness on the deflection is more evident than that of the back face sheet. Increasing the core web thickness and corrugation angle improved the blast performance of panel with a lower deformation, while increasing the core height led to a larger localized deformation at the front face and a lower deflection of back face. Finally, a dimensional analysis based on the experimental results was conducted. Good agreement between the experimental data and the prediction results was obtained by introducing the stand-off parameter and the proposed core supporting parameter.

1. Introduction

Lightweight sandwich structures, with two stiff face sheets and a cellular solid core, have attracted an amount of interest for multifunctional applications to exploit their superior specific strength and impact energy absorption capability [1–7]. In the past few decades, the mechanical properties of sandwich panels have been extensively investigated. Moreover, a variety of micro-architectured materials have been developed to use as cores in sandwich structures due to the development of manufacturing technology. Those include stochastic foam cores [8], triangular honeycomb cores [9], square honeycomb cores [10], hexagonal honeycomb cores [11,12], corrugated cores [13], tetrahedral lattice cores [14,15] and pyramidal lattice cores [16].

Corrugated core sandwich panels have been proposed as an attractive alternate to conventional plate beam metallic structures of a naval ship, since they are light weight, have high longitudinal stretching and shear strengths and exhibit good energy absorption capability [4,17–20]. Chang et al. [21] presented a close-form solution based on the Mindlin–Reissner plate theory to describe the bending behavior of corrugated core sandwich plate. It is found that the variation of corrugation angle can significantly affect the shear stiffness. He et al. [22] divided the real displacement of corrugated sandwich panels into the global displacement field and local displacement field, then conducted a more precise bending stress analysis of corrugated core sandwich panel. Results from the proposed method agreed well with those from detailed finite element analysis. Côté et al. [23] tested the quasi-static out-of plane compressive, transverse shear and longitudinal shear responses of the corrugated cores, and revealed that the corrugated cores can offer comparable longitudinal shear strength to that of pyramidal and square honeycomb cores. Tilbrook et al. [19] investigated the dynamic out-of-plane compressive response of V-type and Y-type corrugated core sandwich panels for impact velocities ranging from quasi-static to 200 m/s. The measured results showed that the dynamic strengthening mechanism of panel was dominated by the inertial stabilization of core webs against buckling when impact velocities is less than 30 m/s. At higher impact velocities, plastic wave effects within the core members will result in the front face stress increasing with the increase of impact velocity while the rear face stresses remain approximately constant. Rejab and Canwell [24] examined the compression response of V-type

* Corresponding author. Tel.: +86 27 87543258; fax: +86 27 87542146.
E-mail addresses: PanZhang@hust.edu.cn (P. Zhang), yscheng@hust.edu.cn (Y. Cheng).

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corrugated core sandwich panels based on an aluminum alloy, a glass fiber reinforced plastic (GFRP) and a carbon fiber reinforced plastic (CFRP). They noted that the initial failure of those three panels was dominated by the instabilities of the cell walls to buckle. The influences of the quantity of unit cells and the cell wall thickness on the compression strength were also evaluated. Using the Optimal Latin Hypercube Sampling (OLHS) techniques and response surface methodology (RSM), Hou et al. [25] optimized the crashworthiness of the corrugated core sandwich panel with the V-type and U-type configurations under low-velocity local impact and planar impact. It is found that the crashworthiness of the optimized V-type panel is slightly better than that of the optimized U-type panel under low-velocity local impact. Moreover, this advantage of V-type panel is more obvious under planar impact. Rubino et al. [26,27] have examined the dynamic response of V-type and Y-type corrugated core sandwich beams and plates by firing metal foam projectiles at the central region. It is found that the sandwich constructions outperform equivalent monolithic counterparts at low levels of projectile momentum. However, this benefits will be compromised with the increase of projectile momentum. Wei et al. [9] found that the sandwich panel with a doubly-corrugated soft core performs better than that with a triangular honeycomb core subjected to localized impulse in water. Rimoli et al. [28] and Wadley et al. [29] tested the deformation and fracture of edge clamped corrugated sandwich panels by the impact of explosively accelerated, water saturated, sand shells. This study revealed the existence of strong coupling between the wet-sand and dynamically evolving shapes of tested panels.

Despite a wealth of literature on the quasi-static and impact loading response of corrugated core sandwich panel, there are relatively few studies on the air-blast response of metallic corrugated core sandwich structures [13,17,30–32]. Xue and Hutchinson [13] conducted three-dimensional finite element (FE) simulations of the dynamic response of clamped sandwich beams with corrugated core. Wiernicki et al. [17] idealized the air blast loading as an equivalent static pressure by using the Dynamic Load Factor (DLF), and presented design solutions for the elastic response and plastic collapse load of metallic corrugated core sandwich panels subjected to air blast loading. Fleck and Deshpande [30] developed an analytical methodology to analyze the structural response of metallic sandwich beams subjected to both air and blasts. Using the analytical model proposed by Fleck and Deshpande [30], Zhu et al. [31] conducted theoretical analysis of the dynamic response of sandwich panel under impulsive loading, and derived some theoretical formulae to predict dynamic response of sandwich panel. Li et al. [32] used a ballistic pendulum to investigate the behavior of two specific configurations of aluminum corrugated core sandwich panels under air blast loadings. The face sheets and cores were made of AL-1200H18, and were joined together with the hot melt adhesive membranes.

In this paper, the experimental results of the laser-welded corrugated core sandwich panels under air blast loading are presented. Particular focus is placed on identifying the influence of the stand-off distance, face sheet thickness, core web thickness, core height and corrugation angle in determining the overall deformation and local collapse behavior of the panels. Attention also focuses on introducing the supporting effect of core into the dimensional analysis to enable a more accurate prediction of mid-point deflection of the panel front face sheet.

2. Experimental procedure

2.1. Materials and fabrication process

The face sheets and corrugated core of the sandwich panel investigated in this study were manufactured from the 304 stainless steel. The desirable mechanical performances (i.e. high ductility, significant strain, and strain-rate hardening) of 304 stainless steel make it well-suited for dynamic loading application, and thus 304 stainless steel was chosen as the base material of test panels. The measured quasi-static (strain rate of the order of $10^{-3}\ s^{-1}$) true stress–strain curve for 304 stainless steel and the appearances of specimens after test are shown in Fig. 1. A summary of the properties of the material is given in Table 1. Fig. 2 shows a sketch of the steel mould used to produce trapezoidal (i.e. U-type) corrugations. The mould was manufactured to a high precision using a computer-controlled numerical milling machine (CNC). However, it was observed from the as-manufactured corrugations that there was some variation in corrugation angle and cell size to the designed values, because of the spring back effect during the unloading process. The global effect of this variation was assumed to be negligible, although it was recognized that this may have a small effect upon the blast performance of panels.

2.2. Unit cell design

The corrugated-core geometry is defined by a repeating arrangement of unit cells, which are determined by a set of geometric parameters. In this study, the unit cell is based on a trapezoidal profile and the corrugated panels consist of several repetitions of an identical unit cell. The geometric parameters identified in Fig. 3a are as follows: t_f and t_b are the front and back thicknesses of the face sheets, respectively; t_c is the thickness of core web; H_c is the height of core; φ is the corrugation angle to the horizontal plane; B_p is the width of the horizontal segment of core; d is the width of unit cell. For the current mould design, the value of B_p was maintained constant at 7 mm. The relative density ($\bar{\rho}$) of the trapezoidal corrugated core is given as:

$$\bar{\rho} \approx \frac{\frac{H_c}{\sin\varphi} + 2t_c \tan\frac{\varphi}{2} + B_p}{H_c \cot\varphi + 2t_c \tan\frac{\varphi}{2} + B_p} \cdot \frac{t_c}{H_c}. \quad (1)$$

2.3. Sandwich panels

A folding technique was used to produce all of the corrugated cores for the sandwich panels. In order to manufacture the corrugations, the stainless steel sheet was placed on the die mould, and then bent under the press force exerted by the punch. After being removed from the mould, the corrugated core were cut by electro-discharge machining (EDM) to the dimensions of 300 mm (L_c, length) × 288 mm (B_c, width). Stainless face sheets were laser cut to the dimensions of 452 mm (L, length) × 440 mm (B, width).

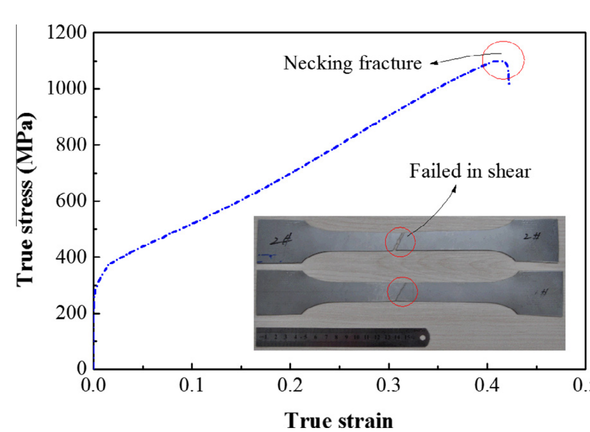

Fig. 1. Static true stress–strain curve for the 304 stainless steel. The specimens failed in shear after some necking.