International Journal of Impact Engineering 65 (2014) 185–194

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

Dynamic response of corrugated sandwich steel plates with graded cores

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ARTICLE INFO

Article history:
Received 4 February 2013
Received in revised form
26 November 2013
Accepted 29 November 2013
Available online 14 December 2013

Keywords:
Carbon steel sandwich plate
Corrugated core
Graded core
Strain-rate dependence
Shock tube test

ABSTRACT

This paper addresses the dynamic response of sandwich steel plates with three kinds of corrugated core arrangements consisting of identical core density subjected to dynamic air pressure loads. The corrugated sandwich steel plate consists of top and bottom flat substrates of Steel 1018 and corrugated core layers of Steel 1008. The corrugated core layers are arranged with uniform and non-uniform thicknesses. The stress-strain relations of Steel 1018 at high strain rates are measured using the Split-Hopkinson Pressure Bar. For dynamic finite element analyses, both carbon steels are assumed to follow bilinear strain hardening and strain rate-dependence. The developed finite element model is validated with a set of shock tube experiments, making it feasible for a parametric design study. Three corrugated core arrangements are taken into consideration for optimizing core design parameters in order to maximize mitigation of blast load effects onto the structure.

1. Introduction

Blasts and explosions may lead to extreme damage to structures and human beings. The blast wave, shrapnel, and heat and fire generated during blast and explosion events are the main causes of damage. To mitigate the damage, the main technology recommendations are the continuity of structures, reserve strength in excess of live loads, redundancy in load bearing paths and increased energy absorption [1,2]. These concepts can be realized by metal-foams [3], sandwich structures [4], polymers [5], and others. This work mainly addresses blast wave propagation and investigates the effects of graded corrugated cores on the dynamic behavior sandwich steel plates in an effort to mitigate the blast effects on the main structure. Much work has been done on the advanced blast-resistant behavior of sandwich structures with different types of cores: such as trapezoid, corrugated, honeycomb, tetrahedral, trusses and pyramidal cores [6–24]. To name a few, Xue and Hutchinson [9] showed that sandwich plates outperform monolithic plates of the same material and the same total mass when subjected to a blast loading. They optimized sandwich structures based on the Taylor's theory with a given face-sheet/core assembly of a specific mass per unit area and subjected to a prescribed momentum impulse per area. Fleck and Deshpande [11,12] used a three-phase analytical model for sandwich plates: the fluid structure interaction phase; core compression phase; and plate bending and longitudinal stretching phase [10]. Their experiments showed that the separation of these phases cannot be assumed for all the cases, and in particular phases 2 and 3 can be coupled [11,12]. The objectives of sandwich plate design and optimization have been to minimize back face deflection, minimize final core compression, increase energy absorption and reduce support reactions [13]. Tilbrook et al. [13] and Liang et al. [14] found that the soft core with a low transverse strength reduces the transmitted impulse during the fluid-structure interaction stage for water blast and increases the coupling between core compression and plate bending, but the soft core can be fully crushed and gives a very high support reaction.

There has been some research done on blast-resistant structures with graded foams or foam-like polymer cores. Avila [25] performed experimental investigation on sandwich plates with a piece-wise functionally graded density core. Apetre et al. [26] investigated the impact damage of sandwich structures with a graded core and found that a reasonable core design can effectively reduce the shear forces and strains within the structures. Shukla et al. [21,27,28] performed shock tube experiment to study the dynamic response of sandwich panels with E-Glass Vinyl Ester composite face sheets and stepwise graded foam cores. The shock tube testing results indicated that monotonically increasing the

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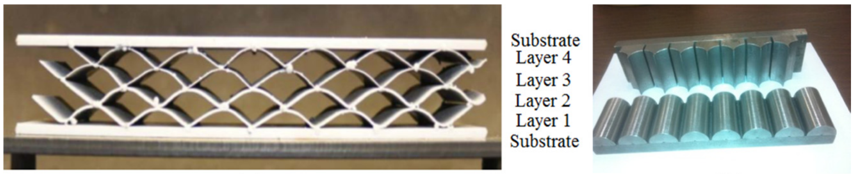
http://dx.doi.org/10.1016/j.ijimpeng.2013.11.011



(a) (b)

Fig. 1. (a) Corrugated sandwich plate and (b) Die used for making corrugated cores.

wave impedance of the foam core from the front (facing shock tube loading) to the back and reducing the wave impedance mismatch between successive foam layers can greatly enhance the overall blast resistance of sandwich composites.

However, little work has been done on the blast responses of sandwich plates consisting of graded corrugated cores. *To this regard, the dynamic response of corrugated sandwich plates with three core arrangements (uniform and graded layer thicknesses) consisting of identical core density are investigated using shock tube testing and finite element simulations*.

This paper is organized as follows. Section 2 describes the corrugated sandwich plate samples with uniform and non-uniform core arrangements. Section 3 presents the shock tube testing performed on corrugated sandwich plates. Section 4 describes finite element modeling procedure to validate the dynamic response of the corrugated layers. Section 5 presents the validated results. Section 6 concludes the work.

2. Sandwich steel plates with corrugated core of uniform and non-uniform thicknesses

The corrugated sandwich plate is envisioned to be attached to main structural components in order to mitigate the blast damage. The corrugated sandwich plate is made of two kinds of low-carbon hypoeutectic steels (Steel 1018 and Steel 1008) and consists of two substrates: front (facing the load) substrate, back substrate, and four corrugated layers as shown in Fig. 1(a). The substrates have the same dimensions, 50.8 mm (width, out-of-plane direction in Fig. 1(a)) x 203.3 mm (length) × 3 mm (thickness) and are 250 g a piece. The substrates are made of Steel 1018 as received, while the corrugated core layers are made of Steel 1008 after heated to 900 °C and furnace cooled, which makes it soft and ductile. The substrates and the corrugated layers are spot-welded together through both ends of the surfaces in contact.

The corrugated core layers are fabricated by repeated corrugation and strengthening using a die shown in Fig. 1(b). The shape of the corrugated layers is approximately a half-sine curve. The height of each corrugated layer is around 6 mm. Uniform and non-uniform thicknesses for the four corrugated layers are considered in this work to investigate the effect of varying thicknesses of the core onto the dynamic behavior. In the following sections, A refers to 0.762 mm, B refers to 0.508 mm and C refers to 0.254 mm having an average mass of 60 g, 37 g and 18 g, respectively. Three core arrangements of the corrugated sandwich plates with identical core density are taken into consideration: BBBB, AACC, and ABBC. Note that the core layering sequence is from back skin to front skin, and the corrugated core layer thickness is designed to increase as it gets closer to the back plate, which is intended to monotonically increase the wave impedance of the core from the front (facing shock tube loading) to the back so that the graded arrangement reduces the wave impedance mismatch between core layers (see Ref. [27] for more information).

3. Shock tube testing of corrugated sandwich plates

Shock tube tests were performed at the University of Rhode Island using the shock tube apparatus (see Fig. 2) [21–23]. The shock tube is divided into a high-pressure driver section and a low-pressure driven section, which are separated by a destructible diaphragm. The driver section is pressurized with high pressure Helium gas which created a pressure difference across the diaphragm. The pressure difference between these two sections becomes higher when pressurizing the high-pressure driver section. When the pressure difference reaches a critical value, the diaphragm ruptures and the resulting rapid release of gas forms a one-dimensional shock wave front. When the shock wave reaches the specimen, the dynamic air pressure load is applied to the specimen [21–23].

The corrugated sandwich plate was simply supported and located with minimal stand-off distance from the nozzle, shown in Fig. 3. The internal diameter of the muzzle is 38.1 mm. The span between the two rigid supports is 152.4 mm. Two rubber bands were also used to bond the specimen to the support in order to avoid their separation prior to the shock tube testing. At least two specimens of each arrangement were tested to ensure reliability.

There were two pressure transducers (PCB102A) mounted at the end of the muzzle section to record the incident and reflected pressure profiles. The first pressure sensor was mounted 180 mm away and the second was mounted 20 mm away from the end of the muzzle, shown in Fig. 4(a).

A typical profile of the incident shock pressure and reflected shock pressure measured during the shock tube testing is shown in Fig. 4(b). The reflected pressure measured by the second pressure sensor was used in finite element modeling. The incident peak pressure of the shock wave was chosen as 0.70 MPa in this study. Due to the fluid-structure interaction during the shock tube testing, the reflected pressure profiles for different corrugated sandwich plates measured by the second sensor were modestly different as shown in Fig. 5. As mentioned earlier, a soft core with a low transverse strength reduces the transmitted impulse during the fluid-structure interaction stage [13,14]. This study demonstrates that the peak pressure magnitude was the lowest in the ABBC core arrangement due to smoothly varying thicknesses from the soft core layer (C–B–B-A) to the back plate.

A high-speed camera system was used to record the motion of the corrugated sandwich plates in order to determine the deflection and velocity histories. The camera system was placed

Fig. 2. The shock tube facility [23].