International Journal of Impact Engineering 62 (2013) 182–195

Contents lists available at SciVerse ScienceDirect

International Journal of Impact Engineering

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

The dynamic response of edge clamped plates loaded by spherically expanding sand shells☆

Kumar P. Dharmasena [a], Haydn N.G. Wadley [a,*], Tao Liu [b], Vikram S. Deshpande [b]

[a] *Department of Materials Science & Engineering, University of Virginia, Charlottesville, VA 22903, USA*
[b] *University of Cambridge, Department of Engineering, Trumpington Street, Cambridge CB2 1PZ, UK*

ARTICLE INFO

Article history:
Received 1 March 2013
Received in revised form
8 May 2013
Accepted 28 June 2013
Available online 13 July 2013

Keywords:
Sandwich panels
Fluid–structure interaction
Impulse loading
Discrete particle simulation
Finite element analysis

ABSTRACT

The dynamic deformation of both edge clamped stainless steel sandwich panels with a pyramidal truss core and equal mass monolithic plates loaded by spherically expanding shells of dry and water saturated sand has been investigated, both experimentally and via a particle based simulation methodology. The spherically expanding sand shell is generated by detonating a sphere of explosive surrounded by a shell of either dry or water saturated synthetic sand. The measurements show that the sandwich panel and plate deflections decrease with increasing stand-off between the center of the charge and the front of the test structures. Moreover, for the same charge and sand mass, the deflections of the plates are significantly higher in the water saturated sand case compared to that of dry sand. For a given stand-off, the mid-span deflection of the sandwich panel rear faces was substantially less than that of the corresponding monolithic plate for both the dry and water saturated sand cases. The experiments were simulated via a coupled discrete-particle/finite element scheme wherein the high velocity impacting sand is modeled by interacting particles while the plate is modeled within a Lagrangian finite element setting. The simulations are in good agreement with the measurements for the dry sand impact of both the monolithic and sandwich structures. However, the simulations underestimate the effect of stand-off in the case of the water saturated sand explosion, i.e. the deflections decrease more sharply with increasing stand-off in the experiments compared to the simulations. The simulations reveal that the momentum transmitted into the sandwich and monolithic plate structures by the sand shell is approximately the same, consistent with a small fluid–structure interaction effect. The smaller deflection of the sandwich panels is therefore primarily due to the higher bending strength of sandwich structures.

1. Introduction

The air and water blast resistance of structures has recently received considerable attention with the overall aim of designing lightweight, blast resistant structures. Several recent theoretical studies have shown that sandwich structures subjected to water blast outperform monolithic structures of equal mass, see for example Refs. [1] and [2]. Experiments reported by Wadley et al. [3] and Wei et al. [4] have confirmed these predictions. The enhanced performance is mainly due to fluid–structure interaction effects such that a smaller fraction of the impulse is transmitted into sandwich structures compared to their monolithic counterparts. By contrast, under air blast, sandwich structures provide smaller benefits over monolithic structures as fluid–structure interaction effects are more difficult to exploit [5–7]. The extension of these ideas to the design of structures that are more resistant to soil impact resulting, from say a landmine explosion, is a topic of considerable interest and the focus of this study.

Several recent efforts have begun to explore the potential of sandwich structures for mitigating the effects of dynamic loadings due to the detonation of a shallow buried explosive [8–10]. The phenomena leading to dynamic loading during such events are complex, but can be separated into three sequential phases: (i) transfer of impulse from the explosive to the surrounding soil/sand, leading to the formation of a dispersion of high velocity particles, (ii) propagation and expansion of the soil/sand ejecta and (iii) impact of the soil/sand ejecta against the structure, with attendant momentum transfer [11]. The experimental characterization of buried explosive events [12–15] has led to the development of

---

* Corresponding author. Tel.: +1 434 982 5671.
E-mail address: haydn@virginia.edu (H.N.G. Wadley).

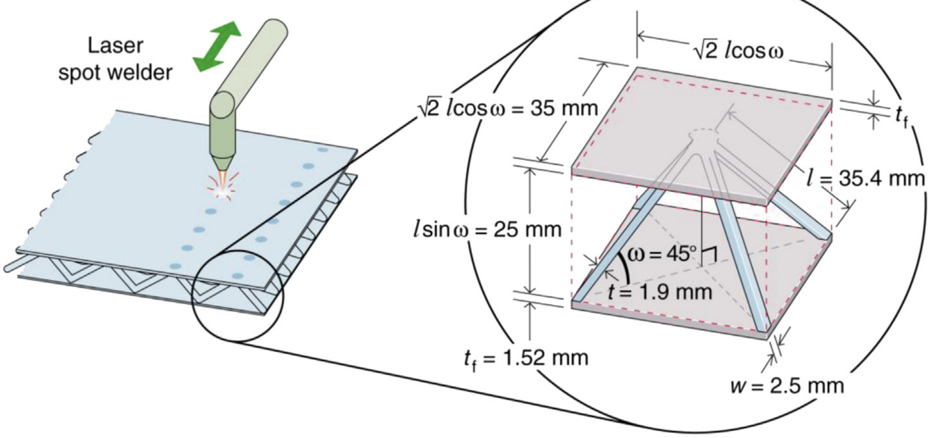
0734-743X/$ – see front matter © 2013 The Authors. Published by Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijimpeng.2013.06.012

empirical models to predict the impulsive loads imposed by soil ejecta [16] as well as to structural design codes such as those proposed by Morris [17]. However, the predictive capability of these empirical models is limited, and they cannot be extrapolated to new structural concepts such as sandwich structures.

In addition to these empirical approaches, a number of numerical codes have been developed in an attempt to predict the response of a structure to soil ejecta. This has focused on the development of appropriate constitutive models for the soil that can be implemented within *Eulerian* numerical codes. The Eulerian codes are then coupled to *Lagrangian* finite element (FE) calculations in order to simulate the structural response. Grujicic et al. [18,19] provide a detailed analysis of the soil models that have been used to simulate landmine explosions. Notable among these are the so-called three phase model of Wang et al. [20,21] which is a modified form of the Drucker–Prager [22] model, and the *porous-material/compaction* model as developed by Laine and Sandvik [23]. The soil models listed above are restricted to a regime where the packing density of the soil is sufficiently high that the particle–particle contacts are semi-permanent. While these models are appropriate during the initial stages of a buried explosion when the soil is shock compressed, their applicability is questionable when widely dispersed particles impact a structure. More recently, Deshpande et al. [8] modified the constitutive model of Bagnold [24] to develop a continuum soil model applicable to soils in both the densely packed and dispersed states. However, the successful implementation of this model within a coupled Eulerian–Lagrangian computational framework has been elusive due to computational problems associated with the analysis of low density particle sprays; see for example Wang et al. [21] for a discussion of these numerical issues.

An alternative modeling strategy has recently been employed by Borvik et al. [9], Pingle et al. [25] and Liu et al. [10], as follows. The low density soil is treated as an aggregate of particles, and the contact law between particles dictates the overall aggregate behavior. This approach has several advantages: (i) there is no need to make a-priori assumptions about the constitutive response of the aggregate (this becomes an outcome of the simulations), (ii) it

a) *Panel assembly unit cell*



b) *Test structure geometry*

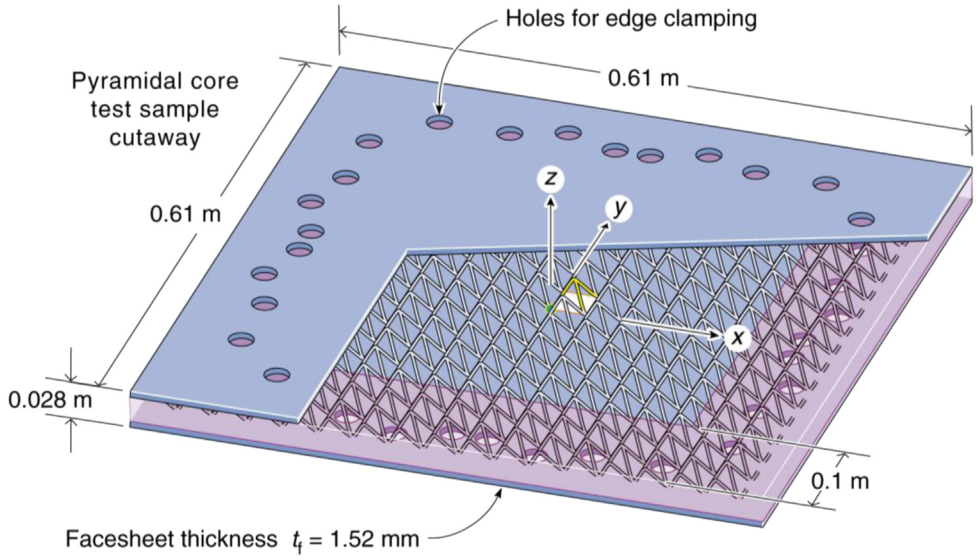


Fig. 1. (a) Sketch illustrating the laser welding process employed to manufacture the pyramidal truss core sandwich panels. A sketch of the pyramidal unit cell with all relevant dimensions labeled is included. (b) The overall dimensions of the sandwich panels.