International Journal of Solids and Structures 51 (2014) 4196–4214

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

Novel stacked folded cores for blast-resistant sandwich beams

M. Schenk, S.D. Guest, G.J. McShane *

University of Cambridge, Department of Engineering, Trumpington Street, Cambridge CB2 1PZ, UK

ARTICLE INFO

Article history:
Received 1 June 2013
Received in revised form 4 July 2014
Available online 23 August 2014

Keywords:
Blast mitigation
Auxetic
Functionally graded material
Sandwich material

ABSTRACT

Recent research has established the effectiveness of sandwich structures with metallic cellular cores for blast mitigation. The choice of core architecture can enhance sandwich performance, dissipating energy through plastic core compression and exploiting fluid–structure interaction effects to reduce the momentum imparted to the structure by the blast. In this paper we describe the first analysis of a novel sandwich core concept for blast mitigation: the stacked folded core. The core consists of an alternating stacked sequence of folded sheets in the *Miura* (double-corrugated) pattern, with the stack oriented such that the folding kinematics define the out-of plane compressive strength of the core. It offers a number of distinct characteristics compared to existing cellular cores. (i) The kinematics of collapse of the core by a distinctive folding mechanism give it unique mechanical properties, including strong anisotropy. (ii) The fold pattern and stacking arrangement is extremely versatile, offering exceptional freedom to tailor the mechanical properties of the core. This includes freedom to grade the core properties through progressive changes in the fold pattern. (iii) Continuous manufacturing processes have been established for the *Miura* folded sheets which make up the core. The design is therefore potentially more straightforward and economical to manufacture than other metallic cellular materials. In this first investigation of the stacked folded core, finite element analysis is used to investigate its characteristics under both quasi-static and dynamic loading. A dynamic analysis of an impulsively loaded sandwich beam with a stacked folded core reveals the versatility of the concept for blast mitigation. By altering the fold pattern alone, the durations of key phases of the dynamic sandwich response (core compression, beam bending) can be controlled. By altering both fold pattern and sheet thickness in the core, the same is achieved without altering the density of the core or the mass distribution of the sandwich beam.

1. Introduction

The response of metallic sandwich structures with cellular cores has been extensively investigated for blast mitigation applications. It has been established that a sandwich structure can outperform an equal mass monolithic plate. Key contributions to sandwich performance include the dissipation of energy through dynamic core compression, and the exploitation of fluid–structure interaction effects to reduce the momentum imparted by a blast (Xue and Hutchinson, 2004; Fleck and Deshpande, 2004; McShane et al., 2007). A wide range of metallic cellular cores have been investigated for this purpose, including: metallic foams (Deshpande and Fleck, 2000; Radford et al., 2006), periodic arrays of bars such as the pyramidal and tetrahedral lattices (Sypeck and Wadley, 2001; Kooistra et al., 2004) and prismatic cores such as the hexagonal honeycomb, square honeycomb and corrugated core (Côté et al., 2004; Côté et al., 2006; Doyoyo and Mohr, 2003; Mohr and Doyoyo, 2004). The dynamic compressive collapse of the cellular core plays an important role in the sandwich response to blast loading (Vaughn and Hutchinson, 2006; Radford et al., 2007; McShane et al., 2012).

In this paper we describe the first analysis of a novel sandwich core suitable for blast mitigation: the *Stacked Folded Core*. The concept is sketched in Fig. 1: individual folded sheets are stacked in alternating layers to form the folded core material. In Fig. 1, the folded sheets lie in the *xy*-plane, with alternating layers stacked in the *z*-direction. A key feature of the proposed concept is the fold pattern of these sheets, the *Miura-ori* (Miura, 2006); by varying the pattern, a rich variety of geometries can be achieved (Khaliulin, 2005). The core geometry is described in Section 2 of this paper, with further details in Schenk and Guest (2013). The stacked folded core offers a number of distinct characteristics compared to alternative sandwich core materials. (i) There is exceptional versatility in the core geometry (via the fold pattern and stacking) to alter the collapse kinematics and hence mechanical properties. (ii) The fold pattern can be continuously varied through the thickness of the sandwich core (while preserving the fold kinematics), permitting

---

* Corresponding author. Tel.: +44 (0)1223 332635.
E-mail address: gjm31@cam.ac.uk (G.J. McShane).

http://dx.doi.org/10.1016/j.ijsolstr.2014.07.027
0020-7683/

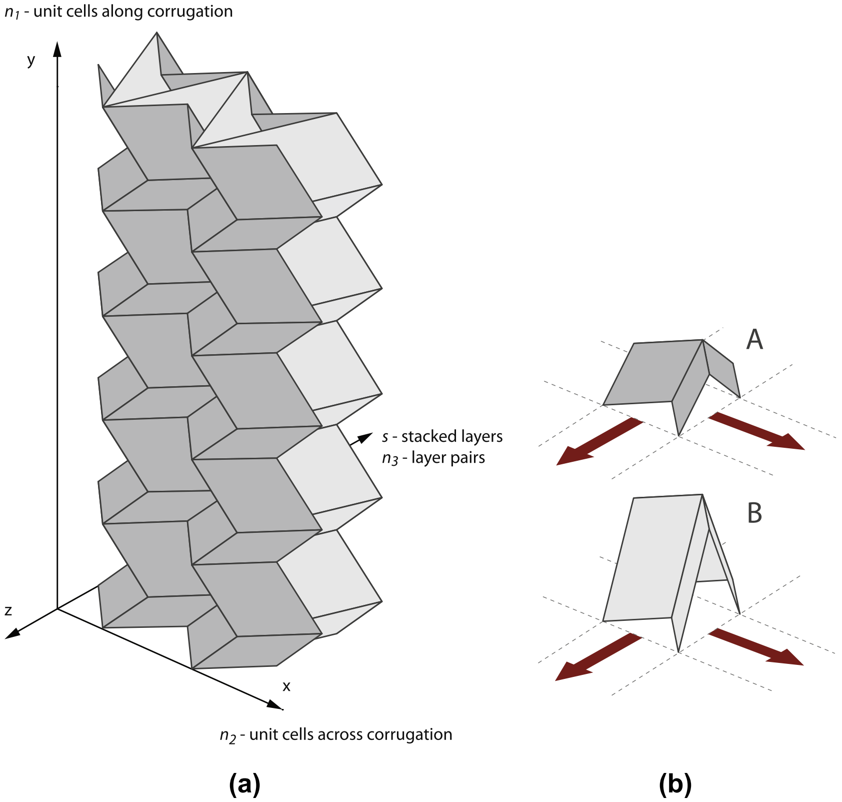

Fig. 1. (a) The geometry of the stacked folded core concept. The folded layers are stacked in the *z*-direction, forming a cellular material defined by: n_1 unit cells along the corrugation, n_2 unit cells across the corrugation, and s stacked layers with n_3 repeating layer pairs. The proposed sandwich core material is oriented with its *y*-axis parallel to the out-of-plane axis of the sandwich panel. (b) Examples of repeating unit cells from adjacent layers of the stack, referred to as layers *A* and *B*. The arrows lie in the *x*–*y* plane, and indicate the direction of tessellation of the unit cells that make up the folded sheet.

graded core properties. (iii) There are established continuous manufacturing processes for the *Miura* folded sheet comprising the core layers. (iv) The core folding kinematics are amenable to application in active or deployable structures. In the following we briefly outline the background to the core development.

1.1. Folded cores

An early example of a sandwich core employing the *Miura-ori* pattern was reported by Rapp (1960), and consists of a single folded layer between two facesheets. Miura (1972) derived expressions for the mechanical properties of the core, and listed among its advantages a high shear modulus and strength, an isotropic or controllable shear modulus, and improved buckling resistance due to the ruled surface along the facets. Lebée and Sab (2010) derived analytical and numerical upper and lower bounds for the shear stiffness of chevron folded core materials in a sandwich panel configuration. There have been a number of experimental and numerical investigations of the large deformation compressive collapse of folded cores, including impact energy absorption (refer to Heimbs et al. (2010) for an overview). It is noted that the buckling of the facets of the folded core play an important role in the out-of-plane compression of the folded sheet. A range of methods to introduce appropriate imperfections to finite element models in order to correctly predict this buckling is discussed by Heimbs (2009) and Baranger et al. (2011). We note, however, that the proposed stacked folded core is less imperfection sensitive, as the collapse mode does not rely on buckling of the facets, but rather the folding kinematics of the folded layers.

1.2. Multi-layer folded cores

An important feature of the proposed concept is the use of multiple layers of folded sheets to create the sandwich core material. Basily and Elsayed (2004) investigated the energy absorbing properties of multi-layered core structures, where folded layers were separated by flat sheets. The folded layers and flat sheets were bonded, to inhibit the unfolding of the cores upon impact. The energy absorption of the core material was investigated for different loading directions, and was found to be equivalent to or outperform similar honeycomb structures. Kling (2010) proposed several methods for stacking and joining the folded layers into multi-layered structures. These include stacking multiple layers of identical folded sheets, or alternating sequences of folded sheets with flat or singly-corrugated sheets. Kling (2010) also recognises that the overall folding kinematics can be preserved when stacking identical folded sheets, creating a customisable cellular material with tailored mechanical anisotropy. In that case, the folded sheets are joined along the fold lines, either by providing a slight offset to glue facets to facets, or creating a local inversion along the ridges to slot the next layer into.

The approach taken in this paper has two key novelties compared to existing folded core materials. (i) In the stacking of folded *Miura* layers, the fold pattern is varied alternately. This allows for a simpler method of bonding the layers whereby each layer simply slots within the fold lines of the previous one. (ii) In using the material as a sandwich core, the stacked layers are oriented so that the folding kinematics of each layer governs the out-of-plane compressive strength and stiffness of the core (the *y*-direction in Fig. 1). Previous research (Tilbrook et al., 2006; Liang et al., 2007; McShane