International Journal of Impact Engineering 84 (2015) 64–77

Contents lists available at ScienceDirect

International Journal of Impact Engineering

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

# The low velocity impact response of sandwich panels with lattice core reinforcement

Jacob M. Hundley*, Eric C. Clough, Alan J. Jacobsen

*Sensors and Materials Laboratory, HRL Laboratories, LLC. 3011 Malibu Canyon Rd., Malibu, CA 90265, USA*

ARTICLE INFO

*Article history:*
Received 23 August 2014
Received in revised form
20 May 2015
Accepted 24 May 2015
Available online 2 June 2015

*Keywords:*
Lattice materials
Cellular solids
Sandwich panel
Finite element method
Homogenization
User material

ABSTRACT

This study presents the experimental and simulation results for the low velocity impact response of sandwich panels reinforced with a lattice core structure. Two different core material and architecture combinations are investigated; a UV-cured photopolymer lattice, produced from a network of self-propagating waveguides, and an aluminum alloy lattice cast from an initial polymer template. For each of these sandwich panel configurations, impact tests were performed with a drop-weight hemispherical impactor under four different energy levels. The applied impact force, impactor velocity and residual damage in the sandwich panel were all measured and used for comparison against finite element simulations of the impact tests. These simulations employed a homogenized continuum constitutive model, designed to replicate the deformation response of the lattice core without requiring explicit representation of the geometric features of the lattice. For both sandwich panel designs at all impact energy levels, excellent correlation was observed between the experimental measurements and impact simulations. Additionally, each sandwich design was shown to be effective at absorbing the kinetic energy of the impactor with minimal damage to the back (non-impacted) face of the panel. Implementation of these lattice core sandwich panels and extension of the homogenized constitutive model to other sandwich applications are also discussed.



## 1. Introduction

Sandwich structures, which consist of two thin, stiff facesheets separated by a low-density core, are often utilized as lightweight reinforcement in applications where high flexural rigidity, buckling resistance, and energy absorption are of interest. In a sandwich structure, the facesheets carry the imparted in-plane loads while the core transfers shear loads between the facesheets and increases the effective moment of inertia of the panel [1,2]. This approach is analogous to a structural I-beam in which the flanges carry applied compressive and tensile loads while the web supports shear loads and spaces the flanges about a common neutral axis. Given the inherent structural efficiency benefits of a sandwich construction, such designs are commonly employed in the aerospace, automotive, marine, and recreational equipment industries.

In all aforementioned applications, selection of the sandwich core is dictated by the competing needs of reducing mass while maintaining adequate stiffness and strength, such that the overall structural requirements are met. Typically, this leads to sandwich cores formed from cellular materials, i.e. materials with significant porosity, whose properties are determined by both material composition and spatial arrangement [3]. While cellular materials such as open or closed cell foams have been used extensively in sandwich designs, recent attention has been focused on core materials with a truss or lattice-type architecture [4–11]. The increased development and analysis of ordered lattice core materials stems from their improved strength and stiffness scaling as compared to randomly distributed architectures such as foams. It has been rigorously demonstrated that cellular materials with randomly distributed architectures deform via non-ideal bending of the cell walls, resulting in stiffness and strength that scale as a function of $\bar{\rho}^n$, where $\bar{\rho}$ is the relative density of the material and $n > 1$. Conversely, when properly designed, ordered lattice architectures deform via stretching of the lattice struts, producing stiffness and strength values which scale as a function of $\bar{\rho}$ [12,13]. The benefits of this improved scaling are especially evident for the low relative densities of interest for sandwich core materials leading to an increased focus on lattice materials in recent literature.

* Corresponding author.
*E-mail address:* jmhundley@hrl.com (J.M. Hundley).

http://dx.doi.org/10.1016/j.ijimpeng.2015.05.009

In order to realize the benefits enabled by architected lattice core materials, the behavior of these cores and the resultant sandwich structures must be investigated under expected in-service loading conditions. For example, impact on one of the sandwich facesheets is a common loading scenario for sandwich structures utilized in the automotive, aerospace, marine, and recreational equipment industries. For an impact event such as a tool drop, low or high speed vehicle crash, or bird strike, the response of the sandwich during the impact event and the durability of the structure post-impact are of interest. It has been shown that sandwich structures demonstrate excellent damage tolerance if the core is properly designed such that it absorbs impact energy via plastic deformation while still retaining sufficient structural rigidity to transfer shear loads between the facesheets [14–17].

In this analysis, we investigate the impact response of lattice core sandwich panels produced using a novel scalable, high-throughput manufacturing process. Two different sandwich core material and architecture combinations are considered; a UV-cured thermoset polymer lattice and an aluminum alloy lattice formed by investment casting of a UV-cured polymer template. For each design, low-velocity impact testing is performed for a variety of incident energy levels using a rigid hemispherical impactor. Impact simulations are also performed, given that the test conditions employed in this analysis are not fully inclusive of all expected impact conditions or all sandwich configurations enabled by this novel manufacturing process. These simulations utilize a homogenized constitutive model developed for lattice structures based on an extension of previous analyses for honeycomb cores [18,19]. The benefit of this homogenized model is that it does not require explicit representation of the lattice structure, which is computationally prohibitive at length scales of practical interest. To validate the homogenized constitutive model, results from the impact simulations are compared against experimental test data for each sandwich configuration and impact energy level. Further extension of these lattice core sandwich structures and modeling techniques to high velocity impact or other multi-axial loading conditions of interest are also discussed.

## 2. Sandwich specimen fabrication

### 2.1. Microlattice core fabrication

In order to evaluate the impact response of sandwich structures employing a lattice core, an efficient and scalable method for producing these highly periodic architectures is needed. In this study, the starting point for each lattice core was a three-dimensional network of interconnected self-propagating photopolymer waveguides. The unique process for producing this waveguide network, hereafter referred to as a microlattice, is detailed schematically in Fig. 1 [20]. As shown in the figure, a liquid photomonomer resin is first placed into a mold cavity which serves to contain the resin and dictate the geometry of the structure to be formed. This mold cavity has a single exposure surface onto which a photo-mask with a defined pattern of two-dimensional apertures is placed. The photomonomer resin is then exposed to collimated UV light through this mask, with the UV wavelength chosen such that it initiates polymerization of the resin upon exposure through the apertures. Polymerization and a subsequent change in the index of refraction between the liquid and solid phases produces a self-focusing effect within the material. Similar to total internal reflection within an optical fiber, UV light tunnels into the polymerized waveguide, which then propagates until it reaches a non-reflecting boundary or until the intensity of UV light is no longer sufficient to induce polymerization. Once the structure is formed, any residual non-polymerized liquid monomer is removed from the mold and recycled as desired.

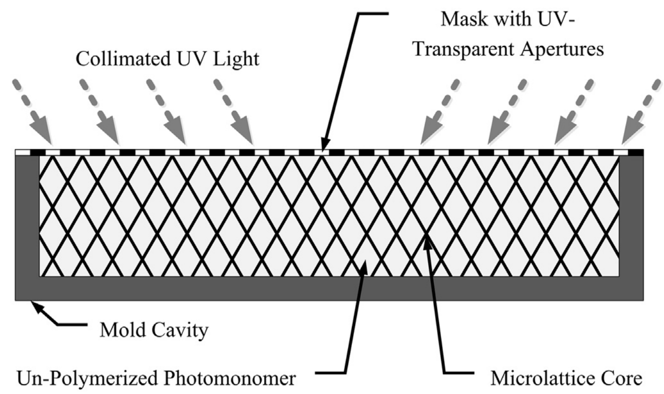


**Fig. 1.** Microtruss fabrication process schematic.

By combining multiple light sources at different orientations and controlling the size, spacing, and periodicity of the apertures in the mask, this process yields enormous design flexibility for three-dimensional lattice architectures. Rapid formation of these microlattice structures is possible because the entire surface of the mask is exposed concurrently, with several orders of magnitude reduction in fabrication time over processes such as stereolithography. Given that the three-dimensional structure is formed in a single exposure and the total area of the part is dictated solely by the size of the UV light sources, exposure times for a single structure on the order of 30–60 s are typical for this process. An example of a single periodic microlattice unit with controllable architecture parameters is shown in Fig. 2.

### 2.2. Microlattice sandwich panel fabrication

To evaluate the impact response of sandwich panels incorporating a microlattice core and validate the homogenized lattice

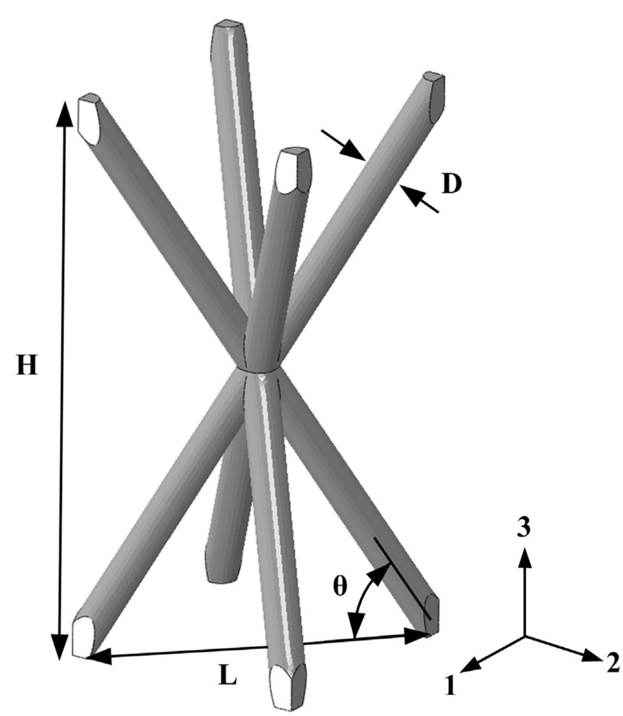


**Fig. 2.** Microlattice periodic unit cell with controllable architecture parameters.