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Designing foam filled sandwich panels for blast mitigation using a hybrid evolutionary optimization algorithm

Idris Karen [a,*], Murat Yazici [b], Arun Shukla [c]

[a] Bursa Orhangazi University, Engineering Faculty, Mechanical Engineering Department, Yildirim Campus 16310, Bursa, Turkey
[b] Uludag University, Engineering Faculty, Automotive Engineering Department, 16059 Bursa, Turkey
[c] The University of Rhode Island, Dynamic Photomechanics Laboratory, Department of Mechanical Industrial and Systems Engineering, 92 Upper College Road, Kingston 02881, RI, USA

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ABSTRACT

Developing sandwich structures with high energy absorption capability is important for shock loading applications. In the present study, a hybrid evolutionary optimization technique based on Multi-Island Genetic Algorithm and Hooke-Jeeves Algorithm is used in the design stage of the sandwich structures to obtain effective results. Optimum parameters of cell geometry were investigated using the hybrid optimization algorithm to design foam filled sandwich panels for three main boundary conditions. Shock tube experiments were conducted in order to simulate the shock load effects along with 3D and 2D finite element analysis. Using the experimental results, a simulation-based design optimization approach was prepared and used to develop the designs of new sandwich structures. Promising results were obtained for all three different boundary conditions. In the simply supported case, 21% improvement of shock absorption was achieved by using 57% less volume of foam with respect to the original fully foam filled sandwich panel. In the clamped-clamped case, 16% improvement of shock absorption with 52% less volume was obtained. In the rigid base case study, 6% improvement of shock absorption with 38% less volume usage was achieved. The structures developed in this study will be of use in the defense, automotive and other industries.

1. Introduction

Recent studies relating to the protection of people from air shock loadings have emphasized the need for the development of novel sandwich structures.

Sandwich structures that consist of different face sheets and cores have been developed to meet suitable shock absorption properties. Of particular interest are metallic sandwich structures composed of cellular material cores that combine high energy absorption capabilities with a lightweight design.

The core material separates the face sheets and provides required stiffness of the sandwich structure. Furthermore, the metallic face-sheets provide the adequate strength for the structure [1–4].

The corrugated metallic core is one of the most popular core topologies in the sandwich panel constructions for blast loading. It provides high strength properties in both the normal and longitudinal directions. The corrugated cores also provide manufacturing advantages; they have an excellent flexibility feature in the design process and beyond, and their low-cost makes the sandwich structures attractive for mass production [5–11].

There is also a growing attention to using the polymeric foams as a filling material to improve the performance and energy absorption capabilities of traditional lightweight sandwich structures [12–17]. By combining a corrugated metallic cellular core with polymeric foams, it is possible to obtain acceptable shock absorption rates and diminish the transmitted shock load. Furthermore, filling the cores with foam supports the core cell walls against buckling and increases the strength of the structure. Filling the interstices of the metallic core sandwich structures with foam also provides some multifunctional advantages such as good acoustic and thermal insulation [12,14,18–21].

Yazici et al. [13] showed that adding foam to the interstices of metallic sandwich panels with corrugated cores doubles the performance of shock load mitigation compared to the unfilled panels. In their further study [14], various preferentially filled core configurations were examined for blast mitigation. Adding the foam to the backside cells of the sandwich structure and leaving the front side cells empty improves the shock absorption performance. Therefore, searching both the optimum core design and optimum foam filling distribution in structures exposed to air shock loading

* Corresponding author.
E-mail address: idris.karen@bou.edu.tr (I. Karen).

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has practical significance in designing a blast-resistant structure that has not been previously investigated.

In this study, the optimum distribution of foam material between corrugated core cells was examined to maximize the performance of the structure. The energy absorption capability of the structure is improved by using a hybrid optimization technique with the aim of increasing the resistance of sandwich panels exposed to blast loads. Also, from the experiments, it is observed that maximizing the energy absorption capability is equal to minimizing the back face deflection (BFD) of the sandwich structure exposed to the shock load.

Applying the optimization methods in the development stage of the sandwich structures is increasing continuously for making brand new structure designs. Some design optimization studies have focused on finding the optimum thermo-mechanical and geometrical parameters of metallic corrugations in the sandwich panel [22,23]. Wadley et al. [1] investigated the optimum topology of metallic sandwich panels with periodic, open-cell cores. Wei et al. [24] searched the optimum design of prismatic core sandwich panels subject to bending loads in the in-plane directions. Rathbun et al. [25] tried to find the optimum core topology between pyramidal truss, tetrahedral truss, square honeycomb, and corrugated sheet. Kooistra et al. [26] applied a design optimization method to find the optimum geometric parameters of second-order corrugated cores. Liu et al. [27] used a quadratic optimizer to determine the optimal dimensions and weights of open-ended, internally pressurized sandwich cylinders. The aforementioned studies were done under static or quasi-static loading conditions. The studies carried out under dynamic loading conditions such as blast loads with high-strain rates are a bit more complex. Liang et al. [28] investigated the optimum geometric parameters of metallic corrugated core sandwich panels subjected to blast loads for the naval industry. Hou et al. [29] used multi-objective optimization techniques for the optimum values of structural parameters of corrugated sandwich panels under low-velocity local impact and planar impact with the crashworthiness criteria. Lim et al. [30] used hybrid sandwich plates for the optimal design of core structure in the sandwich panels against blast loads. Qi et al. [31] used a group of metallic aluminum foam-cored sandwich panels to find the optimum geometric and material design parameters of the structure for vehicle armors against blast loading. In this study, the optimum distribution of foam cores between the metallic corrugation sheets of the sandwich panel exposed to shock loads was investigated using an evolutionary optimization algorithm.

In the literature, different optimization techniques have been developed for various types of problems [32–36]. In recent years, evolutionary algorithms are popular due to their practical, robust and heuristic properties. Because of the nonlinear and non-differentiable properties of dynamical blast-exposed sandwich panel design optimization problems, classical mathematical optimization techniques cannot be used efficiently. These techniques primarily seek the optimum design solution around the starting point and easily get stuck in the local optimum design regions. However, evolutionary algorithms can search throughout the design space efficiently without struggling in local regions. Evolutionary algorithms mimic the laws of nature, especially biological evolutionary processes such as adaptation to rapid changes and intelligent social behaviors of species. These algorithms have been used largely after the 1960s. Among these; Genetic Algorithms [32,33], Differential Evolution [34], Ant Colony Optimization [35] and Particle Swarm Optimization [36] can be listed.

In the present study, a hybrid algorithm based on the Multi-Island Genetic Algorithm and Hooke-Jeeves Algorithm was used as an optimization technique for the purpose of benefiting the powerful properties of two algorithms. Multi-Island Genetic Algorithm [37] is very efficient at global search, whereas the Hooke-Jeeves Algorithm [38] is good at local search. In the hybrid algorithm, these two important properties are combined in such a way that firstly, the Multi-Island Genetic Algorithm explores the design space globally to find a near optimal solution, and then the Hooke-Jeeves Algorithm continues searching the local design space deeply. By this way, the performance of the optimization process was increased significantly.

The optimum distributions of foam filled cells in the sandwich panel core were investigated to develop a novel composite material that has high strength/weight and high rigidity/weight ratios in the design stage of the process. A shock tube apparatus was used in the experiments with high-speed cameras to examine the displacement and strain results of the sandwich structure. A simulation-based design approach integrated with the experimental results was prepared and used for supporting the designs of the new shock absorption sandwich structures. After validating the simulations, the hybrid evolutionary optimization approach was applied, and promising results were obtained for three different boundary conditions; simply supported, clamped-clamped and rigid base case.

2. Experimental study of the fully foam filled sandwich panel subjected to shock loading

The sandwich panel used in the experimental study was prepared with corrugated steel plates containing fully filled foam cores (Fig. 1). Low-density polyurethane (PU) foam was used as a foam material. Each core surfaces were glued by a G/Flex epoxy adhesive (West System Inc., Bristol, RI).

The dimensions of both front face and back face plates are $184.51 \times 50.8 \times 3.175$ mm. A section part of the sinusoidal corrugated steel plates with dimensions in mm is given in Fig. 2.

A shock tube that consists of a long (8 m) thick-walled hollow cylinder was used in the experimental study of the fully foam filled sandwich panel (Fig. 3a). It consists of a driver section with 0.15 m inner diameter, a driven section beginning with 0.15 m and ending with 0.07 m inner diameter, and a muzzle section with 0.05 m inner diameter. The lengths of the sections are 1.82 m, 3.65 m, and 2.53 m, respectively. The driver section is pressurized with helium gas because of its lightweight and non-explosive properties. The driven section has atmospheric air pressure in this case. There is a diaphragm separating the driver and driven sections. The driver section is pressurized until the diaphragm reaches the critical pressure where the rupture occurs. After a rapid release of pressurized gas, the shock wave is created, moving along the tube with a high pressure (incident pressure) and velocity. The shock wave contacts the specimen positioned at the end of the shock tube, reflecting with a higher pressure (reflected pressure) nearly five times greater than the incident pressure. Two pressure transducers are mounted at the end of the muzzle section for mea-

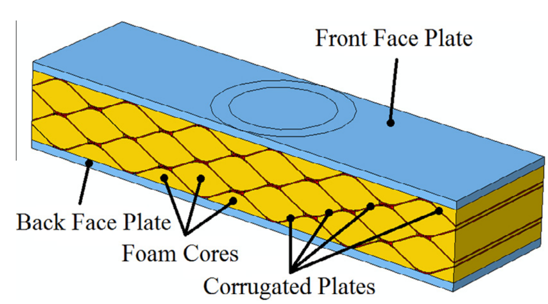

Fig. 1. The sandwich panel with fully foam filled corrugated cores used in the shock load experiments.