Thin-Walled Structures 107 (2016) 197–206

Contents lists available at ScienceDirect

Thin-Walled Structures

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

Full length article

Multiobjective crashworthiness optimization of multi-layer honeycomb energy absorber panels under axial impact

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ARTICLE INFO

Article history:
Received 24 September 2015
Received in revised form
11 June 2016
Accepted 11 June 2016

Keywords:
Multi-layer honeycomb absorber
Crashworthiness
Optimization
Design of experiment
Response surface method

ABSTRACT

In this study, the design and optimization of a multi-layer configuration of hexagonal metal honeycomb energy absorber is performed using the genetic algorithm. It is assumed that the body structure with a predefined velocity impacts with barrier and the design objectives are to absorb whole kinetic energy besides limiting impact shock force. The response surfaces of honeycomb impact characteristics are extracted using finite element approach and then a honeycomb energy absorber is sized for case of a presumed impact problem. A multi-objective optimization technique is adopted to maximize the energy absorption capacity and to minimize the impact shock level while minimizing the total absorber size. A factorial design of experiment and response surface method is utilized to solve the optimization problem. The geometric specifications of honeycomb panels including the cell size, foil thickness, height and absorber face area for each layer of honeycomb panel are assumed as the design variables. Some optimization problems are handled and the optimized designs are compared to those from the literature wherever available.

1. Introduction

Due to the increasing demand for safety in land, sea and air transportation, the low-cost and low-price impact protection is among the indispensable fields of study. To avoid loss of life, any injury or damage during an accident, there is a need for components that can absorb and dissipate the colliding bodies' energy. The energy absorbing substructures are the components used to reduce the unwelcomed effects in accidents. In energy absorbing devices, the kinetic energy prior to impact is transformed into other kinds of energy majorly to plastic strain energy through large deformations of material [1–3]. Honeycomb structures are widely used in various engineering applications (e.g. space, aeronautics, high speed trains and automotive industry) as energy absorbers and protective components, because of their good crashworthiness characteristics of high energy absorption capacity and high strength-to-weight ratio. Due to its low density, high transverse strength and crashworthiness characteristics, the honeycomb structures are recognized as lightweight structural components. In out-of-plane impact direction these structures are more effective in terms of energy absorption while in in-plane directions could be used as soft dampers [2–7]. Metal honeycombs have been successfully used as shock absorbers for example in Apollo 11 moon landing modulus legs [8,9]. A knowledge of structural dynamics besides material mechanical properties is fundamental in the design of components required in withstanding and mitigating mechanical impact conditions. In recent years, many theoretical as well as experimental studies have been published to uncover the mechanical behavior of thin-walled and honeycomb structures during external mass impacts. Most of these investigations have been reported for single layer honeycomb panels.

Yasui [10] has experimentally studied the quasi-static as well as dynamic impact crushing behavior of single and multi-layer honeycomb sandwich panels. The crushed multi-layer panel assemblies have been arranged in uniform type as well as in the pyramid type. In his study, the pyramid-type panel assemblies from two or three basic panel rows have been observed to be the most effective design from the standpoint of energy absorption capacity. Yamashita and Gotoh in 2005 [11] have employed finite element method (FEM) simulation besides experimental methods to investigate the out-of-plane impact properties of aluminum alloy hexagonal honeycomb cores under crushing impact. The numerical simulation has been conducted on a repeatable "Y" cross section column. Deqiang et al. [12] have been studied the functionality of configuration parameters of double-walled hexagonal honeycomb cores (DHHCs) and their out-of-plane dynamic plateau stresses for impact velocity range of 3 to 350 m/s by using ANSYS/LS-DYNA FE simulations. They suggested some empirical expressions on the out-of-plane dynamic mean plateau stresses of

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http://dx.doi.org/10.1016/j.tws.2016.06.008
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DHHCs. They showed that in aluminum double walled hexagonal honeycomb cores, for a given impact velocity out of plane dynamic plateau mean stress is related to the ratio between cell wall thickness and edge length. Li et al. [8] have used metal honeycomb panels as buffering and crushable structures in a lunar lander system and have performed size optimization by using response surface method (RSM). Besides the design optimization procedure, some parametric studies have been carried out to investigate the influence of foil thickness and cell length on the metal honeycombs crushing characteristics. In their study, explicit solver of LS-DYNA FE code has been employed to perform the crashworthiness analyses. Yin et al. [13] have optimized energy absorbers of honeycomb type with various cell specifications. In their optimizing process, the specific energy, and peak crush stress has been aimed as objective functions while the single wall thickness, double wall width and branch angle of the “Y” column have been set as the optimization variables. Xu et al. [6] have experimentally investigated the out-of-plane crushing behavior of four types of aluminum hexagonal honeycomb panels over a wide range of impact strain rates with each test has been conducted at constant compressive velocity. The effects of specimen dimensions, relative density, strain rate, and honeycomb cell size on the mechanical properties of honeycombs have been studied. Also they presented Semi-empirical relations describe the effects of a defined coefficient of relative density and strain rate on the plateau stress. Meran et al. [3] have investigated crashworthiness characteristics of aluminum hexagonal honeycomb structures under impact loads both numerically and experimentally.

In the present paper, sizing of an energy absorber component for a sample moving vehicle (mass) is considered. The manuscript deals with the multi-objective mechanical as well as crashworthiness optimization of the energy absorber sizing. The capability of absorption of energy and simultaneously limiting the shock force besides observing the volume constraints are decided as the key design goals. The energy absorbing facility is supposed as multi-layer aluminum hexagonal honeycomb brick. Firstly, by employing finite element analysis, and a design of experiments approach, the response surfaces of crashworthiness characteristics of the metallic honeycomb (e.g. mean and peak crushing stress) are extracted. The optimization process is then handled by using a genetic algorithm tool to fulfill the objectives of minimizing the absorber volumetric size subjected to peak stress and energy absorption capacity limitation constraints. Geometry specifications including the honeycomb cell size, cell wall thickness, layer heights, and absorber panels' face area are problem variables that will be sized through the optimization process. Since the objective of the optimization is to find the best and smallest absorber unit with highest energy absorption and lowest possible shock level, the multi-objective optimization procedure is formulated for minimization of occupied space subjected to equality constraint of energy to be dissipated and inequality condition of upper shock level limit. It is to be noted that to the best of the authors' knowledge the design and optimization of multi-layer absorber configurations has not been attempted using similar methods elsewhere.

2. Numerical simulation

The single-layer crushable honeycomb structure is numerically simulated. In order to reduce the calculation cost with a complete honeycomb model, the periodicity of the structural pattern is benefited to model simplifying into a variety of unit repeatable cells. The very simplest unit-cell could be handled is a column of “Y”-shape section within a repeating triangular unit-cell area highlighted in Fig. 1. The model consists of three walls intersecting each other in a mutual edge. A single “Y” cross-section shell column that is exhibited to appropriate boundary conditions at the side edges is considered as a representative numerical model for complete reticulated construction of whole honeycomb layer. One of column legs is doubled in thickness in order to demonstrate a real honeycomb wall typically made of two perfectly bonded walls [11,14]. This modeling approach ignores the rare delamination of bonded interfaces and considers the strength of the adhesive bond as infinite.

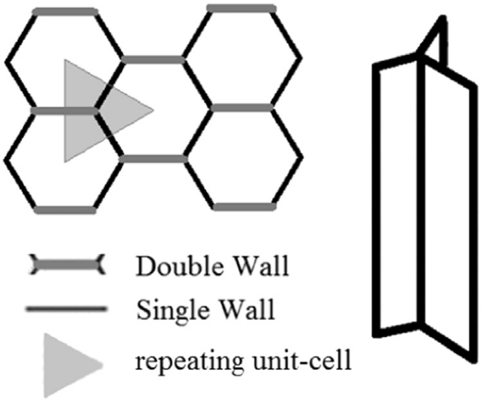

Fig. 1. Honeycomb structural pattern and a repeatable unit-cell with “Y” cross section.

As depicted in Fig. 2, the crushable shell model is positioned between two parallel rigid plates. The top massed plate is moving downward with an initial kinetic energy (velocity of 10 m/s) and is applied to compress the Y-shape column in the axial direction. The bottom rigid surface is totally fixed. Due to the repeatability, there is no difference or priority between any two adjacent cell models from mechanical properties as well as deformation points of view. This fact may be fulfilled through limiting translation in local y direction besides constrained rotation about the local *x* and *z* local directions at three non-intersecting edge nodes on all column walls. As mentioned in Fig. 2, this type of end conditions is called local *y* direction symmetry. Furthermore, all degrees of freedom

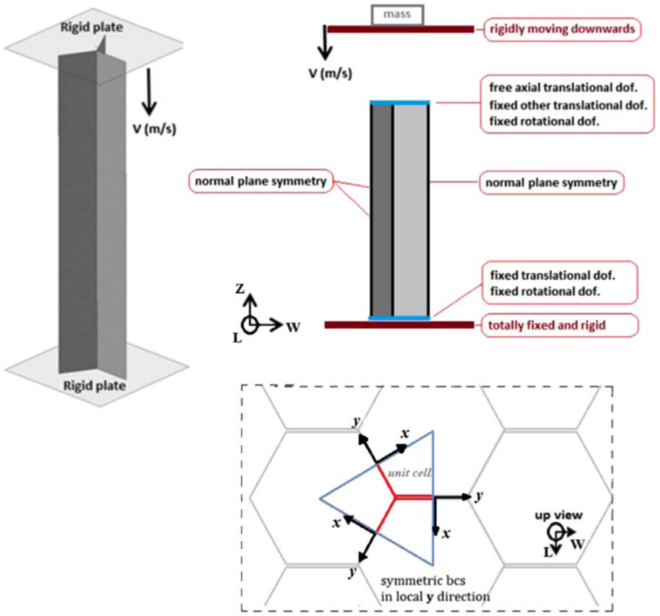

Fig. 2. “Y” column geometrical model, loading and constraints setup.