Composites: Part B 63 (2014) 111–122

Contents lists available at ScienceDirect

Composites: Part B

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

Low velocity transverse impact response of a composite sandwich plate subjected to a rigid blunted cylindrical impactor

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ARTICLE INFO

Article history:
Received 1 September 2013
Received in revised form 14 March 2014
Accepted 23 March 2014
Available online 2 April 2014

Keywords:
A. Layered structures
B. Impact behavior
C. Analytical modeling

ABSTRACT

The low velocity impact problem of a composite sandwich plate impacted by a rigid blunted cylinder is analytically studied. The sandwich plate is composed of laminated face sheets and a rigid-plastic core which can be rigidly supported or simply supported. In contrast to the previous works, the face sheets are with no limitation for the stacking sequence. Also, the effects of in-plane displacement components u and v as well as initial in-plane forces acting on the edges of the sandwich plate are incorporated in the present article. First, by using the minimization of the total potential energy approach, closed form solutions are derived for the static indentation problem and the contact law (contact force–indentation relation) is determined. Then, spring-mass-dashpot models are developed to study the low velocity impact problem. The characteristics of the equivalent spring and dashpot are identified from the derived contact law and by incorporating the effect of the dynamic material properties of the sandwich plate. Analytical predictions for the impact force history are compared well with the experimental and analytical results in the literature. Results of a parametric study show that the stacking sequence of the face sheet has an insignificant effect on both the impact force and the contact duration. Furthermore, if the zero in-plane forces case to be considered as a reference state, the positive in-plane forces increase the impact force and decrease the contact duration, while the negative in-plane forces, with exactly the opposite effects, decrease the impact force and increase the contact duration.

1. Introduction

Structural members built by two face sheets and a light core are known as sandwich panels. Sandwich panels are finding increasing use in aerospace, marine, automotive, transportation and other load-bearing engineering applications. Helicopter blades, optical benches for space applications, nonferrous ship hulls, and future tilt helicopter rotors are some of the applications. Typically, sandwich panels for these applications use thin face sheets bonded to honeycomb or foam cores. Main advantage of sandwich panel is its ability to provide increased bending rigidity without significant increase in structural weight. Other benefits of sandwich panels include excellent thermal insulation, acoustic damping, fire retardation, ease of machining, ease of forming, etc. However, these sandwich panels usually have very low damage resistance and are susceptible to impact damage. The specification, prediction and prevention of the panel's impact damage are significantly important in designing these panels. Although, the damage is not evident, specifically in low-velocity impacts, the structure strength would be affected. Therefore, behavior of impacted sandwich structures is of great attention [1–3].

Although, extensive research has been devoted to the impact behavior of composite laminates in general [2–10], the work on sandwich structures is somewhat limited. In this context, the work of Ambur and Cruz [11] may be mentioned in which a local–global analysis was carried out to determine the contact force and displacement of the panel. In deriving closed-form solution for the impact response of the composite sandwich panels, the composite structures have sometimes been modeled as a discrete dynamic system with equivalent masses, springs and damper. For instance, Shivakumar et al. [12] presented a two-degrees-of-freedom model that consisted of four springs for bending, shear, membrane and contact rigidities to predict the impact response of a circular plate. On the basis of this model, the contact force and the contact duration for low-velocity impact on circular laminates was calculated.

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http://dx.doi.org/10.1016/j.compositesb.2014.03.011
1359-8368/

Other two-degrees-of-freedom models for impact response of composite plates include those by Sjoblom et al. [13] and Lal [14]. Caprino et al. [15] used a single degree-of-freedom system to analyze drop weight impact tests on glass/polyester sandwich panels. Anderson [16] described an investigation using single degree-of-freedom model for large mass impact on composite sandwich laminates. The stiffness parameters of the model were derived from the results of a three-dimensional quasi-static contact analysis of a rigid sphere indenting a multi-layered sandwich laminate. Gong and Lam [17] used a spring–mass model having two degrees-of-freedom in order to determine the history of contact force produced during impact. They included structural damping also in their model.

Malekzadeh et al. [18] introduced a new computational method based on the improved higher order sandwich plate theory (IHSAPT) for face sheets to analyze the transverse low velocity impact on sandwich panels caused by a spherical impactor. Khalili et al. [19] presented a new equivalent three-degrees-of-freedom (TDOF) springs-masses (SM) model, that accommodated normal impact at any location and used it to predict the low-velocity impact response of composite sandwich panels with stiff/flexible core. Their method allowed more than one impactor to act simultaneously on the panel, at different locations, either on the same face sheet or on the opposite sides of the panel. Zhou and Stronge [20] studied the impact response of thin, lightweight circular sandwich panels with simply supported boundaries.

Hoo Fatt and Park [21] used the equivalent single and multi degrees-of-freedom systems to predict the low-velocity impact response of rigidly supported, two-sided clamped, simply supported and four-sided clamped composite sandwich panels. The considered sandwich panels had orthotropic face sheets and were considered to be symmetric. Anderson [22] performed an investigation of single-degree-of-freedom models for large mass impact on composite sandwich laminates. The stiffness parameters of the models were derived from the results of three-dimensional quasi-static contact analyses of a rigid sphere indenting a multilayer sandwich laminate. Energy dissipating elements were included in the models to account for material damage. The validity of the models was examined through comparisons with experimental force history results of impact on six different core and face sheet configurations.

Shokrieh and Fakhar [23] studied the low velocity impact problem of rigidly supported and clamped composite sandwich panels using experimental, numerical and analytical methods. They used a drop weight impact tester to perform the experiments, the LS-DYNA software to do the numerical simulations and equivalent single and two degrees-of-freedom spring-mass-dashpot models to predict the analytical results. The numerical simulation showed a good agreement with experimental data. But, with increasing impact velocity, the analytical model showed some disagreement with experimental results. The possible reason was mentioned as the static analysis and minimization of the potential energy used in the model. Wang et al. [24] studied low-velocity impact characteristics and residual tensile strength of carbon fiber composite lattice core sandwich structures by experimental and numerical methods. Low-velocity impact tests and residual tensile strength tests were conducted using an instrumented drop-weight machine (Instron 9250HV) and static test machine (Instron 5569), respectively. The FE (finite element) software, ABAQUS/Explicit was used to simulate low-velocity impact characteristics and to predict residual tensile strength of the considered sandwich structures. The impact contact force and the tensile strength were accurately estimated. The results showed that the degradation of residual tensile strength can be divided to three stages for different impact energies, and amplitudes of degradation are affected by stacking sequences.

Xie et al. [25] experimentally studied the dynamic response of clamped shallow sandwich arches with core of aluminum foam by impacting the arches at mid-span with metal foam projectiles. Deflection history at the mid-point of the back face sheet and strain history at some representative points on the face sheets were obtained. Deformation mechanisms and deformation/failure modes of specimens were analyzed. Then, effect of key parameters on the structural response of shallow sandwich arches was investigated. Williamson and Lagace [26] performed experiments to study the static indentation and impact behavior of composite sandwich plates. They gauged the face sheet deflection under the indenter and also studied the core and face sheet damages with varying core thickness and laminate lay-up. They found that the load–deflection characteristics and failure predictions under static indentation and low velocity impact tests were similar. Herup and Palazotto [27] performed low-velocity impact and static indentation tests on sandwich plates composed of 4 to 48-ply graphite/epoxy cross-ply laminated face sheets and Nomex honeycomb cores to characterize damage initiation as a function of face sheet thickness and loading rate.

Chai and Zhu [28] reviewed the numerical, mathematical and experimental methods used for the analysis of the sandwich panels subjected to impact loading. They classified the impact responses according to the various key parameters, and listed different methodologies for different classes of impact. The impact responses on sandwich structures were broadly classified into two main groups, high-velocity and low-velocity impacts, with the focus on the low-velocity impact. According to the mass ratio (the ratio of the impact mass to the effective mass of the structural component), the response under low-velocity impact was further subdivided into three possible categories, namely, large, small, and medium mass impacts and for each category of impact, the available solutions were discussed in details. Finally, the review was concluded with detailed discussions on the damage mechanisms and failure criteria for sandwich structures subjected to impact loads.

The indentation of the sandwich panels is predominantly a result of the crushing of the core. So, Hertzian contact laws are inappropriate for the sandwich panels [3,20,21]. In the present study, the correct contact law is firstly derived in which the core crushing is also considered and then it is used in the equivalent spring-mass-dashpot models to predict the low velocity impact response of the composite sandwich plate. In contrast to the previous works, the stacking sequence of the face sheets can be completely arbitrary. Also, the effects of in-plane displacement components u and v as well as initial in-plane forces acting on the edges of the sandwich plate are taken into account. By the present low velocity impact analysis, the deflection and the impact force histories as well as the maximum impact force are obtained. These results can be used to determine the strain and the stress distributions in order to examine the safety of the structure.

2. Problem statement

As shown in Fig. 1, a composite sandwich plate of dimensions $a \times b$, with the laminated face sheets of thickness h and the core thickness H, is considered. The plate is subjected to low velocity impact at the origin by a rigid blunted cylindrical impactor of radius R and length L. The composite sandwich plate can be rigidly supported or simply supported.

According to the deflection to thickness ratio of the top face sheet, three consecutive regimes are considered for the local indentation of the plate [21]. I- Plate on an elastic foundation; II- Plate on a rigid-plastic foundation; III- Membrane on a rigid-plastic foundation. When the indentation is very small, so that the core crushing is elastic, a plate on an elastic foundation can