Composites Part B 107 (2016) 123–140

Contents lists available at ScienceDirect

Composites Part B

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

Nonlinear low-velocity impact response of functionally graded plate with nonlinear three-parameter elastic foundation in thermal field

F. Najafi [a], M.H. Shojaeefard [b], H. Saeidi Googarchin [a, *]

[a] School of Automotive Engineering, Iran University of Science and Technology, Tehran 16846-13114, Iran
[b] Mechanical Engineering Department, Iran University of Science and Technology, Tehran 16846-13114, Iran

ARTICLE INFO

Article history:
Received 6 August 2016
Received in revised form
20 September 2016
Accepted 22 September 2016
Available online 26 September 2016

Keywords:
Nonlinear impact response
Functionally graded material
Nonlinear three-parameter elastic foundation
foundation

ABSTRACT

In this paper a nonlinear investigation is presented for impact response of functionally graded material plates which are resting on a nonlinear three-parameter elastic foundation with simply supported end condition. In foundation, the influence of linear Winkler and Pasternak parameter is taken into account. The governing equations of the plate are derived based on a Reddy's higher order shear deformation theory with the von Kármán-type of kinematic nonlinearity. The effect of thermal field is considered and material properties of the plates are assumed to be temperature dependent, as well and vary along the thickness according to Voigt model. In addition, by using a modified Hertz's contact law, the influence of material properties of the substrate layers on impact response is considered. The equations of motion are solved via an analytical procedure. The effects of deformation theories as well as thermal field, foundation parameters and impactor's parameters are discussed in results and discussion section.

1. Introduction

Solid structures in application fields such as aerospace, automotive, and marine facilities, are susceptible to damages which may be caused by low-velocity impacts of external objects. These impacts may lead to crucial failures, useful life reduction and internal damages [1] which might not be detected through visible observation. Therefore, most of the research have been attempted to understand the effects of such impacts on performance of structures and have focused on increasing the strength of structures against the impact. In order to achieve this, one way is to choose the outer layer material with enough rigidity to bear the impact load, while materials with less rigidity can be used for inner layers to satisfy the economic purposes. Composite materials can provide a properties variation along specific directions to achieve the desired section rigidity in each part of the structures. The available research on the impact analysis of composite structures have been presented based on experimental test, numerical simulations and analytical models. Among the experimental studies, Mines et al. [2] performed a research on the impact behavior of composite panels made from woven glass vinyl ester skins with Coremat core and woven glass epoxy prepreg skins [3] with honeycomb core. They analyzed the energy absorption for different velocities and provided some suggestions for energy absorption rate against the low-velocity impact. Belingardi and Vadori [4] investigated the behavior of glass-fiber-epoxy matrix laminates [5] against the impact force. They analyzed a suitable composite material to dissipate kinetic energy during impacts. Anderson and Madenci [6] conducted impact tests in order to characterize the type of damages occurred in a variety of sandwich configurations with graphite/epoxy face [3] sheets and foam or honeycomb cores. In their study, the results indicated a significant level of internal damage, while the surfaces of both the honeycomb and foam samples revealed very little damage at these levels of impact energy. While conducting an experimental research seems as an appropriate option for more complex geometries, it would lead to limited information and the need for more accuracy to set up the test devices bring a complexity upon the test procedure. A vast majority of the available numerical methods are based on finite element method (FEM) and smooth particle hydrodynamic. Setoodeh et al. [7] investigated impact response of general fiber reinforced laminated composite plates. They utilized FEM with three-dimensional elasticity and layer-wise laminated plate theory. Lin et al. [8] studied a numerical modeling of low-velocity impact of composite multilayered plates using the shell-based smoothed particle hydrodynamics method. However, data process of

* Corresponding author.
E-mail address: hsaeidi@iust.ac.ir (H. Saeidi Googarchin).

http://dx.doi.org/10.1016/j.compositesb.2016.09.070
1359-8368/

numerical simulations require more CPU-time and there might be some complications in modelling and programming of the composite structures. At this point, analytical models would lead to more effective tools since they may provide a parametric study, less computational work and more accurate results in some cases. The most common methods for analyzing the impact phenomenon analytically are based on discrete spring-mass models and Hertz's contact law. Malekzadeh Fard et al. [9] investigated low-velocity impact problem of a composite sandwich plate impacted by a rigid blunted cylinder. They utilized the minimization of the total potential energy approach to derive a solution for static indentation problem and the contact law, they further utilized the spring-mass-dashpot model to analyze the impact behavior of the sandwich plate. Khalili et al. [10] employed classical plate theory (CPT) and an analytical spring-mass model to study the low-velocity impact phenomenon for functionally graded plate with temperature dependent properties. Fatt and Park [11] utilized spring-mass model and developed an equivalent single and multi degree-of-freedom system to predict the low-velocity impact response of composite sandwich panels with general boundary conditions. They provided an analytical solution for transient deformation response of the sandwich panels. Laminated composites have some disadvantages such as the sharp discontinuity in the material properties at interfaces between two different materials. In order to overcome the practical problems of laminated materials, functionally graded materials (FGMs) developed by Koizumi in 1989 [12]. In FGMs, material properties such as density and elastic modulus vary smoothly across specific directions. Due to this characteristic, FGMs offer many advantages such as thermal stresses reduction, high toughness, higher fracture resistance and good machinability [13]. Moreover, for different types of impact phenomenon (i.e. low-velocity, high-velocity and hyper-velocity), FGMs structures might be more efficient in comparison with laminated composites [14]. Several investigation based on various deformation theories such as classical, first order and higher order theories have been conducted to analyzed the vibration [15–20] nonlinear bending [21–26], post buckling [27–31] and low-velocity impact behavior [32–36] of FGMs. Many higher order shear deformation theories have been developed in the last 30 years e.g. Reddy's higher shear deformation theory [37], sinusoidal shear deformation theory [38,39], hyperbolic shear deformation theory [40,41], exponential shear deformation theory [42] and trigonometric shear deformation theory [43,44]. Among the higher order plate theories, the one of Reddy's [45] is considered to be the most popular theory used for analysis of laminated composite plates due to its simplicity and good agreement of its results with 3-D elasticity solutions [46]. This theory is third order plate theory, i.e. the displacement field is assumed to be described by a function of third order.

Structures resting on elastic foundations are becoming increasingly important in many practical problems of engineering such as aircraft, bridge and ship [47], thus, mechanical behavior of laminated plates resting on elastic foundations has been investigated by many researchers. The majority of foundation interactions is modeled using linear Winkler [48], nonlinear Winkler [49] and Pasternak foundation [50] or a combination of them [51–53]. The impact of each foundation parameter might be different for distinctive analysis. For instance, Civalek [54] found that the Pasternak and the nonlinear Winkler foundation parameters have a more significant influence on the dynamic response of the laminated composite plates than linear Winkler parameter. Whereas, for static response of laminated composite plates, nonlinear Winkler parameter has rather less effect on nonlinear response of plate than the Winkler and Pasternak parameters [55]. Lou et al. [56] investigated bending and vibration of a FGM microplate with foundation and showed that linear vibration frequency is unaffected by the nonlinear Winkler parameter. Civalek and Akgöz [57] studied free vibration of micro-scaled annular sector and sector shaped graphene are located on an elastic matrix and showed that the effects of Pasternak parameter were more significant than the effects of the linear Winkler parameter on frequency. While no other investigation has been performed on impact response of FGM plates with nonlinear elastic foundations, a few researches performed on the low-velocity impact of the structures with elastic foundation have been based on simple theories or numerical methods. Wei and Yida [58] investigated the impact behavior of an elastic plate with arbitrary boundary shape supported by a linear viscoelastic Winkler foundation. They extracted impact response equation in the form of nonlinear Volterra integral equation and solved the equation by numerical method. Shariyat and Farazan Nasab [59] used a semi-analytical method with a refined Hertz's contact law to present a solution for eccentric low-velocity impact response of a FGM plate with fully or partially supported edges resting on an elastic foundation. A low-velocity impact analysis of a bidirectional FGM circular plate resting on an elastic foundation was presented by Shariyat and Jafari [60], as well. In this study, a nonlinear analysis is performed for low-velocity impact of FGM plates resting on a nonlinear elastic foundation. Governing equations are extracted based on a Reddy's higher order shear deformation theory (HSDT) with the von Kármán-type of kinematic nonlinearity. An asymptotic method is employed to extract the impact equation. This would lead to a set of highly nonlinear ordinary differential equations. The equations are in parametric form and are solved by fifth order Runge-Kutta-Fehlberg iterative scheme. Novelties of the present research may be summarized as

- Investigation on low-velocity impact of the continuous model of the FGM plates based on HSDT, Considering the effects of a nonlinear elastic foundation on the impact responses, for the first time.
- The most comprehensive form of foundation is considered which is a combination of linear Winkler, nonlinear Winkler, Pasternak foundation parameters.
- Stiffness of the underneath layers are taken into account by determination of the apparent stiffness of the contact region: A modified Hertz's contact law.
- Thermal effect is taken into account and material properties are considered to be temperature dependent.
- The computational time for achieving the solution is significantly lower than other numerical methods. Moreover, the procedure would facilitate a parametric study.

2. Analytical modeling

Fig. 1 shows a FGM plate resting on a foundation and subjected to an external impactor with spherical noise. In order to describe points on the plate, an orthogonal coordinates (x, y, z) is considered which its origin is located on the middle plane at the corner of the plate. Geometric specification of the plate are denoted by dimensions a and b, and thickness h. The initial velocity and radius of impactor are depicted by V_0 and R_i respectively.

2.1. Effective material properties

FGM structures are usually exploited in environments with high temperature gradients and the properties of these constituents are highly temperature dependent. Consequently, It is important to consider gradient of mechanical properties of the FGM structures in different thermal environments [61]. The temperature dependency