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Nonlinear analytical study of thin laminated composite plate reinforced by nanoparticles under high-velocity impact

R. Mohamadipoor[a], M.H. Pol[b], E. Zamani[a,*]

[a] Department of Mechanical Engineering, Shahrekord University, Shahrekord, Iran
[b] Department of Mechanical Engineering, Tafresh University, Tafresh, Iran

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ABSTRACT

An analytical modeling is developed in a range of elastic waves propagation to investigate the nonlinear behavior of thin laminated composite plate. These plates reinforced by nanoparticles under high-velocity impact. Four crucial regions are considered: fracture region, nonlinear deformation region, local movement region and delamination region. In addition, based on a new deformation function, new equations are developed for assessing the normal and shear strains and computing the energy absorbed in different regions. Results of the present study show a good agreement with the available experimental data of other researchers at velocities beyond the ballistic limit velocity (i.e. $V > V_{B.L} \approx 120\,m/s$).

1. Introduction

In recent years, the nanocomposites have been used widely in commercial applications, e.g. space science, and military and aerospace technologies. This is because of the enhanced mechanical properties such as specific strength and stiffness, fracture toughness, impact energy absorption, vibration damping. This improved performance is generally due to the distinctive strengthening of matrix phase and the modification of interfacial properties; e.g. chemical bonds and dispersing of nanoparticles in the phase matrix [1]. One of the critical requirements of the nanocomposite structures during their service life is their protection against high velocity impacts. Therefore, high velocity ballistic impact and its effect on the armour materials have attracted a lot of attention in recent years [2–6]. Among certain studies [7–11], Experimental results show that some nanoparticles can improve the mechanical properties and ballistic resistance of the nanocomposites. Mohagheghian et al. [7] studied the nanocomposite plates with nanoclay, which have been subjected to quasi-static penetration, as well as dynamic impact testing. They demonstrated decreased energy absorption capability of nanocomposite plates in quasi-static testing. Avila et al. [8] studied the effect of nano-clay and nano-graphite on high-velocity impact properties in glass/epoxy. They demonstrated that the addition of nano-clay and nano-graphite plates to laminated glass/epoxy composites increase their resistance to high-velocity impacts. They also exerted a remarkable effect on the fracture mechanism. Naik et al. [9] investigated the effect of adding of nanoparticle on the ballistic impact behavior of unidirectional E-glass/epoxy laminates and epoxy. They observed that V_{50} can be increased by adding nanoparticles. Pol and Liaghat [10,11] conducted an experimental study on the ballistic behavior of glass/epoxy hybrid nanocomposites. Their results show that the energy absorption capability and mechanical properties of the composite are significantly enhanced by adding nanoparticles.

Various studies have been carried out to model the process of penetration of projectiles into targets made of thin composite and nanocomposite plates. These studies have introduced various energy absorption mechanisms, including tensile fiber failure, secondary fiber elastic deformation, kinetic energy of cones formed on the back face of the target, delamination, matrix cracking, shear plugging and friction between projectile and target during the penetration process [12–18]. Among analysis models, Mines et al. [12] and Morye et al. [13] primarily presented those simple models that were based on empirical results. These models, in order to assess ballistic behavior, needed ballistic testing. It was a defect in predicting ballistic behavior and the design of composite structures under ballistic impact. Therefore, Naik et al. [14] presented a completely analytical prediction of the ballistic behavior of woven composite plates by dividing of the ballistic impact time to several intervals. Balaganesan et al. [15] computed the ballistic limit velocity in nanocomposites reinforced with nano-clay particles by Naik et al. [14] model relations. It should be noted that fiber width is substituted with projectile diameter in the strain calculation of Naik et al. model [14]. In addition, Sanchez et al. [16,17] developed an analytical and non-dimensional model based on Morye et al. [13] and Naik et al. [14] model. They used this developed model to study the

* Correspondence to: P.O.B. 115, Shahrekord, Iran.
E-mail address: zamani.ehsan@eng.sku.ac.ir (E. Zamani).

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Nomenclature

A	Cross-sectional area of fracture region
A_{ij}	Extensional stiffness
b	Stress wave transmission factor
$C.C$	Corrective coefficient of delamination region
C_l	Longitudinal wave velocity
C_t	Transverse wave velocity
$C_{1,2,3}$	strain-rate constants
d	Projectile diameter
D	Average flexural stiffness
D_{ij}	Flexural stiffness
e_{xx}, e_{yy}	Normal strain component
e_{xy}	Shear strain component
e_f	Fracture strain of the target
e_{fxi}, e_{fyi}	Strain variations in the fracture region
e_{mxi}, e_{myi}	Maximum normal strain at the impact point along x,y directions within ith time interval
e_{mxyi}	Maximum shear strain at the impact point within ith time interval
$\dot{e}_0$	Quasi static strain rate
$\dot{e}$	Dynamic strain rate
E_0	Quasi-static modulus vector
E_{ij}	Young's modulus
	Effective modulus vector
E_T	Total strain energy
E_{Li}	Total energy absorbed by different mechanisms at the end of ith time interval
$E_{fxi,fyi}$	Energy absorbed by fracture region along x,y directions during ith time interval
E_{fi}	Total Energy absorbed by fracture region during ith time interval
E_{eli}	Energy absorbed by nonlinear deformation region during ith time interval
E_{di}	Energy absorbed by delamination region during ith time interval
E_{bi}	Bending energy during ith time interval
E_{mi}	Membrane energy during ith time interval
E_{KE0}	Initial kinetic energy of projectile
E_{KEi}	Kinetic energy of the projectile during ith time interval
E_{LMi}	Kinetic energy of the local moving part within ith time interval
F_i	Contact force during ith time interval
F_d	Delamination critical load
G_{II}	Strain energy release rate in mode II
G_{ij}	Shear modulus
h	Plate thickness
$ILSS_{G/E}$	Interlaminar shear strength glass/epoxy
L	Length of plate
MC_i	Mass of the local movement during ith time interval
m_p	Mass of the projectile
$M_{x,y,xy}$	The moment resultant
N	Number of time intervals
N_l	Number of layers
N_{fi}	Number of failed layers during ith time interval
$N_{x,y,xy}$	The force resultant
Q_{ij}	Stiffness matrix
r, θ	In-plane polar coordinate
r_d	Delamination radius
r_{li}	Longitudinal wave radius
r_{ti}	Transverse wave radius
S_R	Effective strengths vector
$v_i(r)$	The field velocity at the end of ith time interval
V_i	The projectile velocity at the end of ith time interval
V_s	Initial velocity of projectile
W	The work of external load
ΔZ_i	Central deflection of plate at the end of ith time interval
$W_i(r)$	The local deformation function during ith time interval
x, y	In-plane rectangular coordinates
z	Out of plane rectangular coordinates
ΔZ_i	Central deflection of plate at the end of ith time interval
Δt	Time interval
ρ	Density of the plate
$\sigma_{x,y}$	Normal stress component along x,y directions
τ_{xy}	Shear stress component

ballistic behavior of multi-layered composite plates made of woven glass fibers. They investigated the effect of two dimensionless ratios (geometry and density ratios) on ballistic limit velocity, contact time, and the energy absorption mechanisms. Among the limitations of the previous models [14–17], it is possible to name the uncertainty of strain variations along the thickness and the assumption that all points of the conical region move with one velocity. Then, Pol et al. [18] yielded a more accurate behavior for ballistic impact in 2D woven composite and nanocomposite targets. They determined the relationship for strain variations between different layers of nanocomposite target and investigated the possibility of layer-by-layer fracture during the process of penetration.

As it can be understood from the review of the literature, most analytical models have been considered the ballistic behavior of nanocomposite materials in a one-dimensional form. Due to the limited measurement and no sufficient information, simplistic assumptions are used in this theories. Moreover, in order to calculate the initiation and boundary of the delamination region, a damage threshold, less than the strain of the failure, has been used. In this study, a function is considered that is similar to circular plates under concentrated load by adding the effects of the transverse wave's propagation. Then, with the help of the von Kármán relations in different directions, a simultaneous study of the variations of nonlinear strains is conducted in different regions and thickness direction. Moreover, the variation of velocity, the absorbed energy in different regions, kinetic energy, and delamination are estimated.

2. Mathematical model

2.1. Description of the model assumptions

A number of analytical models have been developed to investigate the behavior of composite targets upon high velocity impacts. However, most of these analytical models are one-dimensional. In the present study, a two-dimensional time-dependent analytical model is developed to predict nonlinear deformations and strains, energy absorption of various fracture modes, amount of delamination damage region of a nanocomposite laminate and residual velocity of the projectile. The following presuppositions have been taken into account in developing this model:

- The stress-strain relationship of the nanocomposite laminates is linear during the impact [18,19]. This assumption is based on empirical observations of stress-strain curve changes during tensile tests of the samples made with different percentages.
- The projectile is rigid and remains undeformed during the ballistic impact [13–17]. This assumption is also taken from the previous observations, which showed that the projectile is not distorted after the high velocity impact [14,18].
- In-plane deformations are little and negligible as compared to the large transverse deformations of the nanocomposite laminate [19,20].

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