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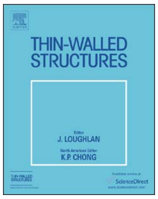

Full length article

Safety assessment of composite beam under ballistic impact

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ABSTRACT

A novel stochastic design approach is presented for a lightweight composite to sustain ballistic projectile impact. Manufacturing of such lightweight composites is a challenging task. Presently, a significant difference is observed in probabilities of failure amongst the four different arrangements of ply lay ups in composite design. The material properties and initial projectile velocity are considered as random parameters. 3D stochastic finite element method is employed to obtain the stochastic dynamic response using explicit time domain solver. The stochastic stresses obtained at critical locations and strength parameters of random nature; contribute to damage initiation. Fiber failure initiation models adopted to establish the performance functions. The probability of failure (Pf) of anti-symmetric cross ply arrangement is found to be minimum in comparison to other ply lay-ups namely, symmetric cross ply, symmetric angle ply and anti-symmetric angle ply. Sensitivity based design optimization is carried out for symmetric cross ply arrangement based on Pf, significantly influenced by the random parameters. This information may be used effectively for design optimization to achieve better strength and lighter weight of composite beam.

1. Introduction

Since the last three decades the usage of composite materials for structure components in the body armors, defense, automobiles and aircraft industry are increasing due to definite advantages in comparison to traditional metallic materials. The most important advantage is the weight of this material based on its low density with accompanying high specific modulus and high specific strength as well as the adaptability to specific applications. However, some of these advantages are compromised when these materials suffer damage due to impact loading. Abrate [1] provided a review that focused specifically on composite beams. The review quite thoroughly outlined the literature related to damage mechanisms in composites during impact and the residual properties of composites after impact. However, it's provided the information of the evaluation of the ballistic limit and residual velocities. Numerical analysis of progressive damage failure model of the laminated composite plate was developed by Yen [2]. In this model, failure initiation and propagation laws were introduced to account the fiber and matrix failure modes. A combined experimental and 3D dynamic nonlinear finite element (FE) approach was adopted by Sevkat et al. [3] to study the damage in composite beams subjected to ballistic impact. The effects of projectile diameter, projectile mass and laminate thickness on the ballistic limit were studied. Iqbal and Gupta [4] investigated the experimental and numerical simulation of aluminum plates up to ballistic limits of different steel projectiles such as blunt-, ogive- and hemispherical-nosed of 19 mm diameter. The impact responses of single and layered aluminum target plates of thicknesses 0.5, 0.71, 1.0, 1.5, 2.0, 2.5 and 3 mm were studied. The ballistic limit of target plate was shown to be considerably affected by the projectile nose shape. Thin monolithic target plates as well as layered in-contact plates were shown to offer lowest ballistic resistance against the impact of ogive-nosed projectiles. Thicker monolithic plates on the other hand, offered lowest resistance against the impact of blunt-nosed projectiles.

A comprehensive literature review highlights several grey areas for further research on dynamic response of composites to projectile impact. Important research aspects missed in the above mentioned literature are the effects of the uncertainties in material properties and initial velocity of impact on failure assessment.

For probability of failure assessment of the composite the simulations for prediction of the failure under impact, need to incorporate these uncertainties. The volume fractions of matrix and fiber, excess amounts of resins in plies or laminates, curing methods, voids and porosity in the matrix, alignment of fibers, bonding between fibers and matrix, temperature effects etc. lead to uncertainty in elastic properties and strength of composites. Guedes Soarse [5] reviewed the work carried out by various authors to investigate the variability arising in the properties of composite materials. Sriramula et al. [6] reviewed the uncertainties in FRP composites and summarized different stochastic

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Nomenclature

B	Stress-Displacement Matrix
Case –I	$[0_3^0/90_3^0]_{2s}$
Case-II	$[0_3^0/90_3^0/0_3^0/90_3^0/0_3^0/90_3^0/0_3^0/90_3^0]$
Case-III	$[45_3^0/-45_3^0]_{2s}$
Case-IV	$[45_3^0/-45_3^0/45_3^0/-45_3^0/45_3^0/-45_3^0/45_3^0/-45_3^0]$
CDF	Cumulative distribution function
CC	Clamped –Clamped
Cu	Copper
$C(x_1, x_2)$	Covariance function
$[C_0]$	Stiffness matrix vector
DIM	Damage initiation model
$D(\mathbf{x}, \theta)$	Approximated elemental matrix
D0	Constant stiffness matrix
E_1	Modulus of elasticity in longitudinal direction 1
E_2	Modulus of elasticity in-plane transverse direction 2
E_3	Modulus of elasticity normal transverse direction 3
E(x)	Stationary Gaussian Process
F	An n × q matrix with rows $H(x_i)^T$
FE	Finite Element
Gc	Critical fracture energy
G_{12}	Modulus of rigidity in 1–2 direction
G_{13}	Modulus of rigidity in 1–3 direction
G_{23}	Modulus of rigidity in 2–3 direction
GPRSM	Gaussian Process response surface method
g(x)	True response function
H(x)	Trend of model
K_e	Elemental stiffness matrix
KL	Karhunen-Loeve
M	Strain softening parameters
M	Number of KL terms
MCS	Monte Carlo Simulation
Pf	Probability of failure
q_{ij}	Damage coupling functions
r_1	Fiber tensile damage threshold
r_3	Fiber compressive damage threshold
r_5	Fiber crushing damage threshold
r_6	Matrix in-plane shear damage threshold
R()	Correlation function
SFEM	Stochastic finite element method
S_{11t}	Fiber tensile strength
S_{11c}	Fiber compressive strength
S_{22t}	Matrix tensile strength
S_{22c}	Matrix compressive strength
S_{33t}	Normal transverse tensile strength
S_{33c}	Normal transverse compressive strength
S_{12}	Strength in shear 1–2 direction
S_{13}	Strength in shear 1–3 direction
S_{23}	Strength in shear 2–3 direction
V	Impactor velocity
w(x)	Expected value
$w(\mathbf{x}, \theta)$	Random process
$[\Omega]$	Undamaged stress matrix vector
$[\varepsilon]$	Strain vector
σ_{11t}	Fiber tensile stress
σ_{11c}	Fiber compressive stress
τ_{12}	Shear in stress 1–2 direction
τ_{13}	Shear in stress 1–3 direction
τ_{23}	Shear in stress 2–3 direction
$\sigma_g^2(x)$	Variance of random parameters **x**
σ_E^2	Process variance
$[\bar{\sigma}]$	Effective stress vector
$[\Omega]$	Effective damage tensor
ϖ_i	Damage variables
ϖ_1	Fiber tensile damage mode
ϖ_2	Fiber Compressive damage mode
ϖ_3	Matrix tensile damage mode
ϖ_4	Matrix compressive damage mode
ϖ_5	Fiber crushing damage mode
ϖ_6	In-plane matrix damage mode
ν_{12}	Poisson's ratio 1–2 direction
ν_{13}	Poisson's ratio 1–3 direction
ν_{23}	Poisson's ratio 2–3 direction
$\varepsilon_{11\,t}$	Fiber tensile strain
ε_{11c}	Compressive tensile strain
ε_{22t}	Matrix tensile strength
ε_{22c}	Matrix compressive strength
ε_{33t}	Normal transverse tensile strength
ε_{33c}	Normal transverse compressive strength,
γ_{12}	Strain in shear 1–2 direction
γ_{13}	Strain in shear 1–3 direction
γ_{23}	Strain in shear 2–3 direction
$\xi_i(\theta)$	Uncorrelated orthogonal random variables
λ_i	Eigen values
φ_i	Eigen functions
β	Vector of trend coefficients
θ_i	Scale Parameter

modeling approaches suggested in the literature. Stochastic studies considered uncertainties starting at the constituent level (micro-scale), ply level (meso-scale) or at a component level (macro-scale). Some authors (e.g. Cederbaum et al. [7], Bucher and Bourgund [8], Chen and Guedes Soarse [9]) performed the probability of failure of composites only under static loads considering different reliability methods such as a first order reliability method, second order reliability method and response surface method. However, these methods failed to estimate the probability of failure accurately in problems with highly nonlinear limit state functions and in problems with low probability of failure, (Rajashekhar and Ellingwood [10]), as higher order terms are neglected. Simulation approaches, like Monte Carlo simulation (MCS), require a large number of FE executions for structural analysis making it computationally expensive, especially for large and complex structures aiming at a high target of reliability (Patel et al. [11,12]). Reliability of composite plate under low and high velocity impact using failure initiation based failure criteria were studied by Ahmad and Gupta [13], Patel et al. [12,14]. The probability of failure of composite plate was carried out using Gaussian response surface method. Gaussian process response surface method (GPRSM) is able to overcome these limitations and leads to a more efficient estimation of probability of failure (Patel et al. [14]).

This research work presents a novel stochastic design approach for a lightweight composite required to be strong enough to sustain ballistic impact due to bullet type projectiles. Fabrication of such lightweight composites is a challenging task. Presently, a huge difference is observed in probability of failure amongst the four different ply arrangements for clamped-clamped boundary condition. Methodology presented can achieve a lightweight composite design using a realistic approach. The present study investigates the dynamic response of a composite beam subjected to ballistic impact. The damage model is implemented in the FE code by a user-defined material subroutine (VUMAT). Stochastic study is performed by considering the variability of material properties (elastic modulus, Poisson's ratio, shear modulus and strength properties) and initial velocity. The probability of failure is carried out using Gaussian process response surface method (GPRSM).