



Nonlinear transient analysis of FGM and FML plates under blast loads by experimental and mixed FE methods

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ABSTRACT

Nonlinear transient behavior of fiber–metal laminated (FML) composite plates under non-ideal blast loads are investigated by both experimental and numerical techniques. In the experiments three plates with different aspect ratios are tested under blast loads and their response is also simulated and compared with both the developed mixed finite element method and the commercial software ANSYS. Furthermore parametric numerical analyses are conducted for nonlinear transient behavior of functionally graded (FGM) thin plates under blast loads with mixed FEM. In these parametric analyses the effect of aspect ratio, load distribution and impulse function in time domain are investigated. In the developed mixed FE formulation, the von Kármán plate theory is used. Nonlinear functional is developed using the Hellinger–Reissner principle and linearized with the incremental formulation. Dynamic analyses are carried using the Newmark method with the Newton–Raphson iterations. Condensation is not performed hence time derivative of internal forces are also calculated during the solutions. Damping is incorporated to the analysis in the sense of the Rayleigh damping. As a result of conducted analyses, there is a good and reliable agreement between the numerical and the experimental results. Moreover, the developed mixed FEM results are almost identical to the ANSYS results.

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1. Introduction

Plate structures have been widely used in aviation, naval defense and nuclear industry as sheathing on the exterior surface of vehicles and structures. The usage of fiber–metal laminates (FML) in these plate structures is increasing day to day and taking the place of traditional composites. FMLs consist of thin metallic sheets bonded to fiber reinforced plastics layers and combine the affirmative features of two different materials without taking the poor fatigue strength of aluminum alloys (or some metals) and the poor impact strength of carbon fibers (or some composites). Advantages of FML can be listed as excellent fatigue behavior, superior impact resistance, inherent resistance to corrosion, good fire resistance, weight reduction and improved damage tolerance characteristics [1,2]. Like as FML, the usage of functional graded materials (FGM) has a trend to increase. FGM idea was proposed in 1980s [3,4] in order to be used in thermal resistant structures. The micro-

structure of FGM is characterized by a spatially varying manner on the macro scale. In thermal barrier structures, FGMs are composed from ceramic and metal. In the thermally more active surface, the ceramic content is richer. Towards to the other surface ceramic content decreases and the metal content increases. The composition of material changes continuously and smoothly throughout the thickness of the plate. All these plates manufactured from FML and FGM are often exposed to uniform or non-uniform blast loads due to the turbulences occurring in atmosphere, explosions, shock waves and sonic booms. Therefore, dynamic responses of these plates under blast loads are still one of the most attractive research areas.

The behavior of plates under blast load was first investigated in [5] with modified Friedlander function. In literature there are many studies that compare the numerical and experimental results of metal plates with and without stiffeners under uniform and localized blast loading [6,7]. In the last few decades, there are also enough researches on the linear and nonlinear behavior of laminated composite plates/shells under blast loads [8–11]. In the recent, the effects of aspect ratio and layer number to the nonlinear dynamic behavior were studied in [12] for the simply supported laminated composite plates.

According to [1] researches on FML structures have started when Faculty of Aerospace Engineering at the Delft University of

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Nomenclature

a, b	plate dimensions in the x, y directions, respectively	$\hat{\mathbf{t}} = \{t_x \ t_y \ t_z\}^T$	traction boundary conditions
a_1, a_2	Rayleigh damping constants	$\mathbf{T}$	transformation matrix
$\mathbf{A}, \mathbf{B}, \mathbf{D}$	Submatrices of the stiffness matrix	u, v, w	midplane displacements in the x, y, z directions, respectively
$\mathbf{A}', \mathbf{B}', \mathbf{D}', \mathbf{H}'$	submatrices of the compliance matrix	$\mathbf{U} = \{u \ v \ w\}^T$	Displacement vector
c_1	power of time function	$\mathbf{X}$	unknown variables
c_2, c_3	power of space functions	x, y, z	Cartesian coordinates
$\mathbf{C}$	damping matrix	z_{t_k}, z_{b_k}	coordinate of the top and bottom surface of the layer k , respectively
$\mathbf{F}$	correction vector	α	shape factor of the Friedlander function
h_+	total thickness of the plate	β, γ	Newmark parameters
$\mathbf{K}_L$	linear system matrix	δII_{HR}	first variation of Hellinger–Reissner functional
$\mathbf{K}$	nonlinear system matrix	$\varepsilon_{xx}, \varepsilon_{yy}, \varepsilon_{zz}, \varepsilon_{xy}, \varepsilon_{xz}, \varepsilon_{yz}$	strain components
L	total number of layers	$\boldsymbol{\varepsilon}^0 = \{\varepsilon_x^0 \ \varepsilon_y^0 \ \gamma_{xy}^0\}$	in-plane strains
$\mathbf{M}$	mass matrix	$\boldsymbol{\varepsilon}^u$	strain components in terms of displacements
$\mathbf{M} = \{M_x M_y M_{xy}\}^T$	bending moments	$\boldsymbol{\varepsilon}^\sigma$	strain components in terms of stresses
n	volume fraction exponent	ϕ_i	bilinear shape functions
$\mathbf{N} = \{N_x N_y N_{xy}\}^T$	in-plane forces	$\boldsymbol{\kappa}^0 = \{\kappa_x^0 \ \kappa_y^0 \ \kappa_{xy}^0\}^T$	curvatures
$P(x, y, t)$	blast load function	$\theta_x, \theta_y, \theta_z$	rotations around the x, y, z axes, respectively
$P_t(t)$	blast load function defining the distribution in the time domain	ρ	density of the plate material
$P_s(x, y)$	blast load function defining the distribution in the space domain	$\boldsymbol{\sigma} = \{\sigma_{xx} \ \sigma_{yy} \ \sigma_{xy}\}^T$	stress components
p_0	peak value of the blast load	$\boldsymbol{\sigma}^\sigma = \{N_x N_y N_{xy} M_x M_y M_{xy}\}^T$	internal force vector
p_p	peak pressure value of the blast load	$(\dots)$	first time derivative of the variable
p_s	peak suction value of the blast load	$(\dots)$	second time derivative of the variable
$P(z)$	distribution of the material property	$(\dots)$	increment in the variables
P_c	corresponding ceramic properties	$(\dots)_i$	value of variable in the node i
P_m	corresponding metal properties	$(\dots)^{(i)}$	iteration number indices
p_{eq}^k	equivalent effective property of the layer k	$(\dots)_k$	layer indices
$\mathbf{q} = \{q_x \ q_y \ q_z\}^T$	external load vector	$P(\dots), t(\dots)$	variables belong to initial load and time step, respectively
$\mathbf{Q}$	externally applied load	$p + \Delta p(\dots), t + \Delta t(\dots)$	variables belong to load and time step after increment, respectively
$\Delta \mathbf{Q}$	external load increment		
$\mathbf{Q}$	elasticity matrix in plate axes		
$\mathbf{Q}^*$	elasticity matrix in material axes		
t	time		
Δt	time increment		
t_p	duration of pressure load		

Technology introduced ARALL (Aramid Reinforced Aluminum Laminate) in 1978 and GLARE (GLASS Reinforced) in 1990. Linear and nonlinear dynamic behavior of FML composite panels were investigated experimentally and theoretically in [13]. Dynamic response of FML cylindrical shells subjected to initial combined axial load and internal pressure were studied in [14]. The dynamic response of FML panels subjected to uniform and localized blast loading is also become an attractive research area and investigated experimentally and numerically in [15–21].

In recent years, numerous researches about FGMs have been conducted for their usage in aerospace and nuclear reactors. Nonlinear static and transient behavior of FGM plates under pressure loads and temperature distributions are investigated in [22,23] by using finite element methods based on first and high order shear deformation theories. FGM plates and shallow shells are analyzed in [24] with Fourier series under transverse mechanical loads and a temperature field. Nonlinear bending analysis of FGM plates with temperature dependent material properties are investigated in [25] with a semi-numerical approach based on multi parameter perturbation technique. Element-free kp-Ritz method is used in [26] for the nonlinear analysis of FGM plates. Also nonlinear bending, vibration and post buckling behavior of FGM plates are investigated in [27–31] among others. Most of the studies with FGM plates are conducted under suddenly applied uniform loading and only very few of them investigated non-uniform and impulsive load conditions. Linear transient response of FGM thin plates with

and without Pasternak type foundation under partially distributed impulsive pressure loads are investigated in [32] with modal superposition method. In the study five different impulsive load functions in the time domain are used. Also in [33,34] the nonlinear static bending response of FGM plates under uniformly and sinusoidally distributed transverse loads are compared.

In this study, nonlinear transient behavior of fiber–metal laminated composite plates (FML) under non-ideal blast loads are investigated by both experimental and numerical techniques. In the experiments three plates with different aspect ratios are tested under blast loads and their response is also simulated and compared with both the developed mixed finite element method (FEM) and the commercial software ANSYS. Furthermore parametric numerical analyses are conducted for nonlinear transient behavior of functionally graded thin plates (FGM) under blast loads with mixed FEM. In these parametric analyses the effect of aspect ratio, load distribution and impulse function in time domain are investigated. According to the knowledge of authors, there is no work for nonlinear transient analysis of FML and FGM plates by the mixed FEM.

Three FMLs of different aspect ratio are produced by using wet lay-up with vacuum bagging technique and then cured in a heated vacuum curing table. In the experiments, non-ideal and non-uniform blast pressure is obtained using a shock tube. FMLs are placed in front of the shock tube with clamped edges. The increase of air pressure in the shock tube results in tearing of the membrane

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