International Journal of Mechanical Sciences 83 (2014) 30–37

Contents lists available at ScienceDirect

International Journal of Mechanical Sciences

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

Stress wave micro–macro attenuation in ceramic plates made of tiles during ballistic impact

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ARTICLE INFO

Article history:
Received 2 January 2013
Received in revised form
11 February 2014
Accepted 21 March 2014
Available online 27 March 2014

Keywords:
Ceramics
Ballistic impact
Planar stress wave propagation
Stress wave attenuation
Micro attenuation
Macro attenuation

ABSTRACT

Stress wave attenuation studies during ballistic impact are presented for longitudinal tensile waves propagating along the planar direction within a ceramic plate made of hexagonal tiles bonded with an adhesive. When a stress wave reaches an interface between the ceramic tile and the adhesive layer, reflection and transmission of the incident stress wave takes place leading to attenuation of the wave. This is because of impedance mismatch at the ceramic–adhesive and adhesive–ceramic interfaces. This phenomenon is referred to as macro attenuation. Reflection and transmission of the impact induced stress waves would also take place at the interfaces between grains and grain boundaries within the ceramic plate. This would also lead to attenuation of stress waves, and is referred to as micro attenuation. Micro attenuation is modeled using the stress wave attenuation coefficient. Stress wave attenuation studies are carried out based on both micro and macro attenuation. An algorithm is presented for tracking impact induced planar stress waves and predicting their intensities and extent of attenuation. It is observed that stress wave attenuation is significant as the waves propagate within the ceramic plate. A combination of micro and macro attenuation would give the correct estimate of planar stress distribution around the point of impact.

1. Introduction

The transverse ballistic impact onto a target by a projectile generates compressive and shear stress waves along the thickness direction and tensile and shear stress waves along the planar direction [1]. Through the thickness compressive and shear stress waves generated would lead to initiation and propagation of damage in the target along the thickness direction. Another equally important consideration during ballistic impact is the extent of damage around the point of impact along the planar direction. The intensity of planar longitudinal tensile stress waves would determine the extent of in-plane damage.

The impact induced stress waves undergo reflection and transmission when they reach any interface across which impedances are different. Stress wave reflection and transmission, in case of ceramic plates, can be of two types, one, at the structural level [1] and two, at the grain level [2]. An example of the first type is the transverse ballistic impact of a projectile on to a ceramic–composite armor made using bonded ceramic tiles. In this case, reflection and transmission of impact induced longitudinal tensile stress waves take place at the ceramic–adhesive and adhesive–ceramic interfaces along the planar direction. Reflection and transmission of stress waves also take place at the ceramic–composite backing plate interface along the thickness direction. Multiple such reflections and transmissions of the incident stress waves would lead to attenuation of stress waves at the structural level. This phenomenon is referred to as macro attenuation [3]. An example of the second type is reflection and transmission of impact induced stress waves at the grain–grain boundary interface in ceramic plates due to difference in elastic properties and density of grain and grain boundary. A grain boundary is the interface between two grains, or crystallites, in a polycrystalline material. Impedance mismatch between grain and grain boundary would also lead to attenuation of stress waves, referred to as micro attenuation [2]. Micro attenuation is modeled using a material property referred to as stress wave attenuation coefficient. Stress wave propagation and attenuation characteristics are required for modeling a system and simulating it for different applications.

Barker [4] developed a theoretical model to describe transient and steady state stress wave propagation in laminated composites. The dispersive effects in the composite were accounted for by direct analogy with a viscosity effect in the model. Barker et al. [5] further validated the theory using results from experiments in which a low volume fraction of aluminum was used in a PMMA/aluminum based layered system.

Lundergan and Drumheller [6] performed analytical and experimental investigations on stress wave propagation in a laminated

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http://dx.doi.org/10.1016/j.ijmecsci.2014.03.020
0020-7403/

composite. One-dimensional wave propagation codes were used to analyze the problem and make comparisons with experimental results. Sve [7] studied the effect of geometric dispersion and spatial attenuation operating simultaneously, on the shape of a stress pulse as it propagates through an elastic body. He concluded that the relative importance of these two mechanisms determines the rise time, maximum amplitude and shape of the stress wave.

Daniel et al. [8] performed experimental investigations to determine wave propagation characteristics of unidirectional (UD) and angle ply composite laminates impacted with silicon-rubber projectiles. Strain gauge signals were used to determine the attenuation characteristics. Roylance [9] performed experiments on UD graphite/epoxy laminates to assess their resistance to dynamic loading. It was found that the stress pulse attenuated exponentially with distance. He proposed that attenuation was due to hydrodynamic catch-up and void crushing.

Ting [10] developed an analytical solution for transient stress response of waves propagating in a semi-infinite viscoelastic layered composite. A scalar parameter was defined which contained information about the influences on the wave profile due to dissipation, dispersion and the distance traveled by the wave. Clements et al. [11] studied a unit cell method for analyzing wave propagation in systems having complicated internal cell structure. They generalized this method to include viscoelastic materials such as polymers and systems simulating actual impact experiments. The theory was validated by comparing the results with measurements from a flat-plate impact experiment on a system made of epoxy and epoxy-graphite subcells.

Chen and Chou [12] studied transient elastic wave propagation in woven-fabric composites under impact loading. One-dimensional analysis was carried out to predict the elastodynamic and elastostatic behavior. The initial boundary value problem was solved using Laplace transform. Later, Chen et al. [13] solved the same problem using a new approach based on Laplace transform and finite Fourier transform.

Parga-Landa et al. [14] developed an analytical model to simulate propagation of a stress wave in the thickness direction due to impact on a composite material. One-dimensional wave propagation theory was used. Han and Sun [15] proposed a short-time relaxation function for analyzing stress wave attenuation in a periodically layered elastic medium. They studied both, the wave front decay and the spatial attenuation of stress waves in a periodically layered medium. They concluded that a higher impedance mismatch between the two constituent materials leads to higher spatial attenuation of waves.

Benatar et al. [16] proposed an approach to solve the Pochhammer frequency equation to describe propagation of longitudinal elastic waves in cylindrical rods. They formulated corrections for geometric dispersion for both the phase velocity and attenuation. Biwa et al. [17] carried out theoretical analysis of wave attenuation characteristics of UD fiber-reinforced polymer composites using a micromechanical differential incremental scheme. The analysis yielded the attenuation of the wave because of both wave scattering loss due to the composite microstructure and the viscoelastic absorption loss.

Chen et al. [18] developed an analytical solution to the problem of one-dimensional wave propagation in layered material systems based on Floquet's theory of ordinary differential equations with periodic coefficients. They obtained the stress-time history by formulating the problem as a time-dependent stress boundary value problem. They thus accounted for the multiple wave interactions at the heterogeneous interfaces. Results from the analytical model were validated by comparing with numerical results obtained from a shock wave based finite element code and experimental data. Aggelis et al. [19] investigated the dispersive and attenuative behavior of fresh cementitious material. They observed that attenuation is mainly due to the effect of sand particles and entrapped air bubbles. Pandya et al. [20] performed experimental studies on in-plane stress wave attenuation in woven fabric composites under ballistic impact loading.

During ballistic impact event, the target offers resistance to penetration/perforation of the projectile into it. Consequently, contact force is generated between the projectile and the target. The projectile and the target would be moving forward during the ballistic impact event. The incident kinetic energy of the projectile would be absorbed by the target through various damage and energy absorbing mechanisms. In other words, energy transfer would take place from the projectile to the target. Through the thickness compressive and shear stress waves generated would lead to initiation and propagation of damage in the target along the thickness direction. This would lead to penetration/perforation of the target by the projectile. The various damage and energy absorbing mechanisms for a ceramic target impacted by a projectile are: compression and crushing of the ceramic directly below the point of impact, shear plugging of the target around the periphery of the projectile and formation of ring and radial cracks due to tensile stress in the region surrounding the impacted zone. Erosion and deformation of the projectile are the other possible energy absorbing mechanisms. As a result of these damage and energy absorbing mechanisms, the kinetic energy of the projectile, in turn, the velocity of the projectile would be decreasing. This would continue until either the projectile velocity becomes zero within the target or the projectile exits the back face of the target with certain exit velocity. At ballistic limit velocity, the tip of the projectile would be reaching the back face of the target with zero velocity.

Through the thickness stress waves determine important penetration/perforation characteristics and ballistic impact parameters such as ballistic limit velocity and contact duration.

Another equally important consideration during ballistic impact is the extent of damage around the point of impact along the planar direction. In other words, shape and size of the damage zone around the point of impact is an important parameter for damage tolerance characteristics of the target. The intensity of planar longitudinal tensile stress waves would determine the extent of in-plane damage.

Even though there are typical studies on stress wave propagation/attenuation in layered heterogeneous media, the effect of reflection and transmission of stress waves at interfaces on attenuation is not fully understood. A combination of micro and macro attenuation would give the correct estimate of stress distribution around the point of impact.

The objective of the present study is to investigate planar longitudinal stress wave propagation and attenuation during ballistic impact in ceramic plates made of hexagonal tiles bonded with an adhesive. The attenuation studies are performed considering stress wave transmission and reflection at the micro and macro interfaces across which impedances are different.

Specifically, distribution of planar longitudinal stress wave intensity is determined assuming unit incident longitudinal stress wave intensity. In other words, the studies are based on unit step loading of infinitesimal duration and reflection and transmission of stress waves at the interfaces at both structural and grain levels along the planar direction.

During ballistic impact, compressive and shear stress waves are generated in the target along the thickness direction and tensile and shear stress waves are generated along the planar direction. The intensity of stress waves travelling along the thickness direction (direction of impact) would be greater than the intensity of stress waves travelling along the planar direction (normal to the direction of impact). It should be noted that only planar longitudinal tensile stress wave propagation/attenuation is considered