International Journal of Solids and Structures 48 (2011) 1219–1228

Contents lists available at ScienceDirect

International Journal of Solids and Structures

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

Multi-scale damage state estimation in composites using nonlocal elastic kernel: An experimental validation

Amit Shelke [a,*], Sourav Banerjee [a], Tribikram Kundu [a], Umar Amjad [b], W. Grill [b]

[a] Department of Civil Engineering and Engineering Mechanics, University of Arizona, Tucson, AZ 85721, United States
[b] Institute of Experimental Physics II, University of Leipzig, Germany

ARTICLE INFO

Article history:
Received 10 August 2010
Received in revised form 23 November 2010
Available online 14 January 2011

Keywords:
SHM
Composite
Lamb wave
Non-local Christoffel equation
Nonlocal parameter
Precursor to damage detection

ABSTRACT

In recent years early detection of structural damage (detecting incubation of damage) has received great attention in the structural health monitoring field. However, extraction of lower scale information to quantify the degree of damage is a challenging task, especially when the detection is based on macro-scale acoustic wave signals. All materials exhibit dependence on the intrinsic length scale. An attempt is made in this paper to extract lower scale feature from the macro-scale wave signal using nonlocal elasticity theory. The Christoffel solution has been modified using nonlocal parameters. The dispersion curves are generated for anisotropic solids using perturbation parameter through nonlocal theory. Dispersion curves are sensitive to initiation of damage in anisotropic solids at the intrinsic-length scale. In this paper detection of initiation of damage in a 4 mm carbon composite plate is demonstrated by employing nonlocal perturbation parameter and formulating a new Nonlocal Damage Index (NDI). The nonlocal theory is used to demonstrate the early prediction of failure of the system and to show progressive evolution of the damage.

1. Introduction

Carbon fiber composite materials are the most popular alternative structural materials in the aviation industry. However, the composite materials are susceptible to internal or interfacial damages during the operation and maintenance. These damages may occur due to impact events or damage growth under variable and repeated loading conditions. Such initiation of damage results in accumulated micro voids, matrix cracking, eventually delamination and component disbond etc. Continuous evaluation of the damage sites using embedded and in situ damage diagnosis systems are the inevitable solution towards monitoring the health (Qing et al., 2007) of the structure. However, there are many challenges that are associated with detecting the incubation of damage before the damage manifests at the macro scale. Large impacts can cause serious delamination in composites and can be detected very easily. However, low velocity impacts and also the regular use induce damages that cannot be detected so easily. Such damages are incipient and can cause catastrophic failure if unnoticed at the earlier stage. Carbons composites have high frequency dependent attenuation. Therefore usually low frequency guided Lamb waves are used for damage detection in carbon composites. However, such low frequencies are not sensitive to the damages which are smaller than the wavelength of the propagating wave.

Mal et al. (1991) experimentally and theoretically showed that reflection spectra are strongly affected by delamination in composite plates. Chimenti and Martin (1991), Ditri et al. (1992), Guo and Cawley (1993), Kundu et al. (1996), Maslov and Kundu (1997) and Wang and Chang (1999) have utilized various sensors for generating ultrasonic Lamb waves in composites and developed different damage detection frameworks.

It is well known (Kim and Grill, 1998), that small changes in the time of flight (TOF) of in propagating wave modes are related to the perturbation originating from the atomic scale. Grill et al. (1996, 2010) and Wolfe (1998) have systematically demonstrated through several experimental investigation that at frequencies >80 MHz the change in TOF of Lamb wave is highly sensitive to the micro changes in the materials in comparison to the changes in amplitude of the transient signals.

It has been established that almost all material behaviors show strong dependency on the length scales. However, classical elasticity theories are independent of the length scale and are insufficient to predict the behavior at variable temporal and spatial scales. It is inevitable that the guided wave signals saturating the structure is not independent of the material length scale. Lack of consideration of scaling laws in materials modeling creates some ambiguity in the material response (Bazant and Planas, 1998). The stress singularities at the crack tip and non dispersive behavior of the waves at high frequencies are few of the discrepant behaviors

* Corresponding author. Fax: +1 520 621 2550.
E-mail addresses: amitsh@email.arizona.edu (A. Shelke), souravb@acellent.com (S. Banerjee), tkundu@email.arizona.edu (T. Kundu), amjad@physik.uni-leipzig.de (U. Amjad), grill@physik.uni-leipzig.de (W. Grill).

0020-7683/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ijsolstr.2011.01.003