Composites Science and Technology 69 (2009) 2392–2409

Contents lists available at ScienceDirect

Composites Science and Technology

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

Review

Energy absorption capability of nanocomposites: A review

Lingyu Sun [a], Ronald F. Gibson [b,*], Faramarz Gordaninejad [b], Jonghwan Suhr [b]

[a] School of Transportation Science and Engineering, Beijing University of Aeronautics and Astronautics, Beijing 100191, PR China
[b] Department of Mechanical Engineering, University of Nevada, Reno, Nevada 89557, USA

ARTICLE INFO

Article history:
Received 20 March 2009
Received in revised form 23 June 2009
Accepted 24 June 2009
Available online 30 June 2009

Keywords:
A. Nanocomposites
B. Impact behavior
B. Interface
B. Fracture toughness
C. Crack

ABSTRACT

Experimental evidence shows that some nanocomposites with special matrices and filler materials may achieve significant and simultaneous improvements in stiffness, fracture toughness, impact energy absorption and vibration damping, and these characteristics could be of particular importance in automobile or airplane structures. This paper reviews relevant literature which deals with various manifestations of energy absorption of composites from the nano to the macro-scale, with emphasis on the nano-scale. Energy absorption mechanisms in nanocomposites will be examined, along with important influence factors, such as shape, dimension and stiffness of particles, type of matrix, particle volume fraction, distribution of particles and the particle–matrix interfacial properties by both experiments and simulation methods. Relevant potential applications will be discussed, and the key related issues that need to be resolved in the future will be addressed.

Contents

* Corresponding author. Tel.: +1 775 784 1489; fax: +1 775 784 1701.
E-mail address: ronaldgibson@unr.edu (R.F. Gibson).

0266-3538/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compscitech.2009.06.020

1. Introduction and overview of energy absorption in composites

Energy absorption is an increasingly important function of structural materials for several reasons. For example, structural crashworthiness is now an essential requirement in the design of automobiles, rail cars, aircraft and rotorcraft. The crashworthy structure is designed such that in the event of a crash, it absorbs the impact energy in a controlled manner before the energy gets transmitted into the passenger compartment. Traditionally, metals have been the most commonly used materials for crashworthy structural applications, mainly due to their plastic deformation characteristics that enable them to absorb impact energy in a controlled manner [1]. Unlike metals, polymer composite materials do not typically exhibit plastic deformation, although their stress–strain relationships may show signs of other types of nonlinearities, but they are superior to metals for specific energy absorption. Polymer-based nanocomposites offer the potential for simultaneous improvement of several properties, including toughness [2]. Other manifestations of energy absorption in structural materials are internal damping, which is important for the control of vibrations and fatigue, and fracture toughness, which is a measure of the energy required for crack growth and fracture.

When the dimensions of the reinforcement fibers or particles approach the nanometer scale, a number of effects cause the properties of the corresponding composites to be different from those of composites reinforced with macro-scale particles. The main factors affecting the properties of nanocomposites include nano-filler dispersion, dimensions, volume fraction, the nature of the matrix material, the interfacial characteristics between nano-filler and matrix, and the manufacturing process [3].

At present, most of the research results on energy absorption in composites have relied on experiments and by varying design parameters, such as the type of filler, size or volume fraction [4,5]. However, it is not easy to intuitively predict the energy absorption properties of the resulting nanocomposites due to the anisotropic properties and morphology of the nano-particles. Thus, it is desirable to carry out analytical or numerical analyses to understand how particles affect the mechanical behavior of the composite. Various approaches including molecular dynamics simulations, continuum mechanics, elastic shell theory, and finite element analysis have been investigated. However, due to theoretical limitations, the aforementioned modeling methods have their own shortcomings [6]. Multi-scale analyses have been conducted for nanoparticle-reinforced polymeric composites by incorporating molecular mechanical models into continuum models in recent years [6].

Although numerous new nanocomposites have been developed in various research fields, the research on energy absorption capability of nanocomposites is still in the early stages. There are several technical issues to be addressed: (1) lack of acceptable evaluation parameters and methods for energy absorption capability of nanocomposites, such as evaluating indicators, test methods and test conditions; (2) lack of theoretical models that can predict the energy absorption capability; (3) lack of a systematic comparison of limitations and advantages among the existing research methods; (4) lack of a fundamental understanding of energy absorption mechanisms in nanocomposites; (5) need for finding potential applications of energy-absorbing nanocomposites.

The purpose of this work is to review relevant literature related to energy absorption of composites having constituent dimensions ranging from the nano-scale to the macro-scale, with emphasis on the nano-scale. Energy absorption mechanisms in nanocomposites as well as key design factors, effective experiments and simulation methods will be reviewed. Moreover, potential applications will be discussed, and the key technical issues that need to be solved in the future will be also addressed. While review articles and even books on energy absorption in conventional composites have been published [7–11], the authors concluded that a review article on energy absorption in nanocomposites has not yet been published, and that such an article should be of significant value to the composites research community.

2. Experimental characterization of energy absorption in composites

In the following, two key concepts will be discussed: (1) structural energy absorption capability and, (2) material properties which are related to the material energy absorption capability. Two common tests [7] are often used for examining the energy-absorbing capabilities of composite structures: the axial crush [1] and bending crush [12] tests of thin-walled structural components.

Axial crush tests can be carried out under either quasi-static loading or impact loading. The static axial collapse tests can be performed between the parallel steel plates of a hydraulic press at very low crosshead speed, such as 1 mm/min, while the corresponding dynamic tests can be conducted by a direct impact using a drop hammer or an impactor. Due to its simplicity, many researchers have used the quasi-static test [1]. Although the cross section of the samples may have various geometries [13–17], most experiments on polymer composites have been carried out using axisymmetric cylindrical tubes, mainly because they are easy to fabricate. Typical dimensions of composite tubes are 50–100 mm length, 50 mm internal diameter and 2–3 mm wall thickness. Limited results are also available on flat plates [18], sine webs [14], cones [15], square and hexagonal tubes [16]. The typical crushing deformation modes of composite tubes in axial compression are shown in Ref. [19]. Similar tests in bending can be performed using three- or four-point loading of composite tubes or shells.

The energy absorbed by the collapsed specimen during the axial crushing process is calculated by measuring the non-recoverable area (not including the recoverable elastic strain energy) under the corresponding load, P, versus shell shortening (displacement) s curve. The total area under the curve, including both recoverable and non-recoverable areas, is given by

$$W = \int P ds \tag{1}$$

and the non-recoverable area is $W_p = W - W_e$, where W_e is the elastic strain energy.

The energy absorption capability of an axially loaded shell of a given material is typically quantified by the specific energy absorption (SEA), specific absorbed energy (SAE) or special energy (E_s). This is defined as the ratio of the energy absorbed, W_p, for the collapsed specimen, to the crushed mass, m_c, which is calculated as the crushed volume, v_c, times the material density ρ.

$$SEA = \frac{W_p}{m_c} = \frac{W_p}{\rho v_c} \tag{2}$$

The SEA has been widely used to evaluate the energy absorption capability of structures [20–24]. Assuming that such tubes could be manufactured using nanocomposites, their SEA values could be obtained from crush testing to evaluate energy absorption capability. However, no publications on crushing of nanocomposite tubes have been found, and this appears to be an area in need of exploration. Other related material properties, such as the impact strength [3,25], notched Charpy or Izod impact toughness [2], fracture toughness [26–28], strain energy release rate [29], fracture en-