ARTICLE IN PRESS

Composites: Part B xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Composites: Part B

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

Energy absorption capability of carbon nanotubes dispersed in resins under compressive high strain rate loading

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ARTICLE INFO

Article history:
Received 20 September 2014
Received in revised form 15 November 2014
Accepted 18 November 2014
Available online xxxx

Keywords:
A. Nano-structures
A. Particle reinforcement
A. Thermosetting resin
B. Impact behavior
High strain rate testing

ABSTRACT

The focus of the present study is on energy absorption capability (E_A) of carbon nanotubes (CNTs) dispersed in thermoset epoxy resin under compressive high strain rate loading. Toward this objective, high strain rate compressive behavior of multi-walled carbon nanotube (MWCNT) dispersed epoxy is investigated using a split Hopkinson pressure bar. The amount of MWCNT dispersion is varied up to 3% by weight. Calculation methodology for the evaluation of E_A of individual CNTs and CNTs dispersed in resins/composites is presented. Quantitative data on E_A of individual CNTs and CNTs dispersed in resins under quasi-static and high strain rate loading is given.

1. Introduction

Carbon nanotubes (CNTs) offer scope for the development of nanoparticle dispersed resins and composites with excellent mechanical properties, for day-to-day as well as high technology applications. The mechanical properties of carbon nanotube (CNT) dispersed resins and composites under quasi-static loading have been reviewed [1–5]. It was observed that CNT dispersed resins/composites display superior mechanical properties compared to those without CNT dispersion. The addition of CNTs does not lead to significant weight penalty. Recently the use of nanoscale fillers such as CNTs to enhance the energy absorption capability of resins/composites has been considered. There is a need to understand the influence of energy absorption characteristics of CNTs on the impact response of lightweight materials. Toward this, studies are available in literature on high strain rate behavior of CNT dispersed resins and composites [6–8].

For their effective use in high performance applications, the behavior of structural materials under high strain rate loading should be fully understood.

Studies are available in literature on quasi-static behavior of individual CNTs [9–13]. They include experimental investigations, molecular dynamics (MD) simulations and structural dynamics based approaches. Further, studies are available on quasi-static and high strain rate behavior of CNT dispersed resins/composites [14–16].

Pandya et al. [17] provide a qualitative description of damage and energy absorbing mechanisms of CNTs and CNT dispersed resins/polymer matrix composites under quasi-static and high strain rate loading. However, to our knowledge, no studies are available on quantification of energy absorption capability of CNTs under high strain rate loading.

The focus of the present study is on energy absorption capability of CNTs dispersed in resins under compressive high strain rate loading. Toward this objective, high strain rate compressive behavior of multi-walled carbon nanotube (MWCNT) dispersed thermoset epoxy is investigated using a split Hopkinson pressure bar (SHPB) apparatus [18,19]. In the present study, energy absorption capability of CNTs is quantified based on the energy absorbed per unit volume by CNTs. Quantitative data on energy absorption capability of CNTs dispersed in resins under high strain rate loading is presented. Comparison of energy absorption capability of CNTs under quasi-static and high strain rate loading is also presented.

2. Energy absorbing capability of carbon nanotubes

Energy absorbed per unit volume (E_A) by individual CNTs and CNTs dispersed in resins/composites is presented in Table 1.

Given experimental, MD simulation or structural mechanics based stress–strain curve of individual CNTs, energy absorbed by CNTs per unit volume is,

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http://dx.doi.org/10.1016/j.compositesb.2014.11.026
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Please cite this article in press as: Pandya KS, Naik NK. Energy absorption capability of carbon nanotubes dispersed in resins under compressive high strain rate loading. Composites: Part B (2014), http://dx.doi.org/10.1016/j.compositesb.2014.11.026

Nomenclature

d	outer diameter of CNT
D	amount of CNT dispersion in resin by weight
E	energy absorbed by CNT
E^C	energy absorbed by CNT dispersed composite
E^P	energy absorbed by plain composite
E_A	energy absorbed by CNT per unit volume
E_A^C	energy absorbed by CNT dispersed composite per unit volume
E_A^P	energy absorbed by plain composite per unit volume
ΔE	additional energy absorbed due to presence of CNTs
ΔE_A	additional energy absorbed due to presence of CNTs per unit volume
F	force on CNT
F_C	force on CNT dispersed composite
F_P	force on plain composite
l	length of CNT
s	displacement of CNT
s_C	displacement of CNT dispersed composite
s_P	displacement of plain composite
s_{ult}	ultimate displacement of CNT
s_{ult}^C	ultimate displacement of CNT dispersed composite
s_{ult}^P	ultimate displacement of plain composite
V_C	volume of composite
V_{CNT}	volume of CNT
V_f	fiber volume fraction
ε	strain of CNT
ε_C	strain of CNT dispersed composite
ε_P	strain of plain composite
ε_{ult}	ultimate strain of CNT
ε_{ult}^C	ultimate strain of CNT dispersed composite
ε_{ult}^P	ultimate strain of plain composite
ρ_{CNT}	density of CNT
ρ_m	density of matrix
σ	stress on CNT
σ_C	stress on CNT dispersed composite
σ_P	stress on plain composite

$$E_A = \int_0^{\varepsilon_{ult}} \sigma d\varepsilon \tag{1}$$

where σ and ε are stress and strain of CNT, respectively and ε_{ult} is ultimate strain of CNT.

Given experimental or MD simulation based force–displacement curve of individual CNTs, energy absorbed by CNTs per unit volume is calculated as,

$$E = \int_0^{s_{ult}} F ds, \quad E_A = E/V_{CNT}, \quad V_{CNT} = \pi d^2 l/4 \tag{2}$$

where E is energy absorbed by CNT, F and s are force and displacement of CNT, respectively, s_{ult} is ultimate displacement of CNT. Here, V_{CNT}, d and l are volume, outer diameter and length of CNT, respectively.

Given experimental or MD simulation based stress–strain curve of CNT dispersed resins/composites, energy absorbed by CNTs per unit volume is calculated as,

$$E_A^P = \int_0^{\varepsilon_{ult}^P} \sigma_P d\varepsilon_P, \quad E_A^C = \int_0^{\varepsilon_{ult}^C} \sigma_C d\varepsilon_C, \quad \Delta E_A = E_A^C - E_A^P, \quad \Delta E = \Delta E_A V_C \tag{3a}$$

where E_A^P and E_A^C are energy absorbed per unit volume by plain composite and CNT dispersed composite, respectively. Here, σ_P, ε_P and ε_{ult}^P are stress, strain and ultimate strain of plain composite, respectively while σ_C, ε_C and ε_{ult}^C are stress, strain and ultimate strain of CNT dispersed composite, respectively. ΔE_A is additional energy absorbed per unit volume due to presence of CNTs. ΔE and V_C are additional energy absorbed due to presence of CNTs and volume of composite, respectively.

$$\text{Volume of resin in composite} = (1 - V_f)V_C$$

$$\text{Weight of resin in composite} = (1 - V_f)V_C\rho_m$$

$$\text{Weight of CNTs in composite} = (1 - V_f)V_C\rho_m D$$

$$\text{Thus, } E_A = \Delta E_A \rho_{CNT}/(1 - V_f)\rho_m D \tag{3b}$$

where ρ_{CNT} and ρ_m are densities of CNT and matrix, respectively. V_f and D are fiber volume fraction and amount of CNT dispersion by weight in matrix, respectively.

Given experimental or MD simulation based force–displacement curve of CNT dispersed composites, energy absorbed by CNTs per unit volume is calculated as,

Table 1
Energy absorption capability of individual CNTs and CNTs dispersed in composites.

Sr. No.	Material	Method used[a]	Loading[b]	E_A (GJ m^{-3})	E_A (10^9 eV m^{-3})	References
(a) Individual CNTs						
1	SWCNT	Experimental tensile stress–strain curve	QS	0.55 (0.13–1.25)	0.09 (0.02–0.20)	[9]
2	MWCNT	Experimental tensile stress–strain curve	QS	1.62 (0.25–2.60)	0.26 (0.04–0.42)	[10]
3	SWCNT	Structural mechanics based tensile stress–strain curve	QS	5.70 (4.20–7.20)	0.91 (0.67–1.15)	[11]
4	SWCNT	Structural mechanics based compressive stress–strain curve	QS	13.60 (11.90–15.30)	2.18 (1.91–2.45)	[11]
5	MWCNT	MD simulation (tension)	QS	3.60	0.58	[12]
6	SWCNT	Experimental tensile force–displacement curve	QS	0.76	0.12	[13]
(b) CNTs dispersed in composites[c]						
1	MWCNT dispersed epoxy	Experimental tensile stress–strain curve	QS	0.08	0.01	[14]
2	SWCNT dispersed epoxy	Experimental tensile stress–strain curve	QS	1.97	0.32	[15]
3	MWCNT dispersed polycarbonate	Compressive SHPB stress–strain curve	HSR	0.72	0.12	[16]

Values in round brackets indicate scatter band.

[a] MD = molecular dynamics, SHPB = split Hopkinson pressure bar.

[b] QS = quasi-static, HSR = high strain rate.

[c] Energy absorbed for the loading condition considered.

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