Polymer Testing 32 (2013) 1334–1341

Contents lists available at ScienceDirect

Polymer Testing

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

Material properties

High strain rate in-plane shear behavior of composites

H.L. Gowtham, Jayaram R. Pothnis, G. Ravikumar, N.K. Naik*

Aerospace Engineering Department, Indian Institute of Technology Bombay, Powai, Mumbai 400076, India

ARTICLE INFO

Article history:
Received 28 June 2013
Accepted 10 August 2013

Keywords:
In-plane shear properties
High strain rate
Split Hopkinson pressure bar
Off-axis testing
Compression
Tension

ABSTRACT

Studies are presented on in-plane shear properties of a typical plain weave E-glass/epoxy composite under high strain rate loading. In-plane shear properties were determined with ±45 degree off-axis compression and tension tests using a split Hopkinson pressure bar apparatus. In-plane shear properties are presented as a function of axial and shear strain rates. The range of axial strain rates for off-axis compression tests was 819–2003 per sec, and for off-axis tension tests was 91–180 per sec, whereas the range of shear strain rates for off-axis compression tests was 1388–3442 per sec and for off-axis tension tests was 153–303 per sec. In general, it was observed that in-plane shear strength was enhanced at high strain rate loading compared to that at quasi-static loading. Also, it was observed that in-plane shear strength increased with increasing strain rate within the range of strain rates considered.

1. Introduction

Composites can be tailor made for a unique combination of mechanical, thermal and chemical properties. These materials are finding increasing uses in high performance as well as in day-to-day applications. The basic requirement for any engineering material or structure is to withstand the load it is subject to. During the designed life, any structure would undergo a variety of loading conditions. The behavior of any material/structure varies with the type of load applied. Likewise, the response of composite materials/structures to dynamic loading is substantially different compared to that at quasi-static loading.

For effective use of composites in dynamic applications, understanding the behavior of composite materials/structures at high strain rate loading is essential. Fundamental modes of load application for any structure both in quasi-static or dynamic mode are tension, compression and shear. Since composites are orthotropic materials, studies on interlaminar shear (ILS) and in-plane shear (IPS) properties are necessary.

Several methods have evolved over time to test shear properties under quasi-static as well as dynamic loading [1]. The focus of the present study is on IPS characterization of a typical plain weave E-glass/epoxy composite under high strain rate loading. Split Hopkinson pressure bar (SHPB) testing is widely used for such studies [1–4], while ±45-degree off-axis specimens give accurate IPS behavior for plain weave fabric composites [5].

In the present study, IPS properties are determined using ±45 degree off-axis compression and tension tests performed on SHPB apparatus. For compression testing, results are generated using signals obtained from strain gauges mounted on the incident and transmitter bars, whereas for tension testing, results are generated using signals obtained from strain gauges mounted on the incident and transmitter bars as well as on the specimen.

Studies available in literature on IPS behavior of composites under quasi-static and dynamic loading conditions are presented in brief below.

Initial studies under quasi-static conditions were conducted by Chamis and Sinclair [6] to determine the suitability of using 10 degree off-axis specimens to evaluate

* Corresponding author. Tel.: +91 22 2576 7114; fax: +91 22 2572 2602.
E-mail address: nknaik@aero.iitb.ac.in (N.K. Naik).

0142-9418/$ – see front matter
http://dx.doi.org/10.1016/j.polymertesting.2013.08.008

Table 1
In-plane shear properties of composite materials under quasi-static loading (from literature).

Material	Shear strength, (MPa)	Ultimate shear strain, (%)	Shear modulus, (GPa)	Technique used [Reference]
UD Mod-I/ Epoxy	59.2	0.95	6.1	Off-axis tension test [Chamis and Sinclair (1977)]
UD Carbon/ Epoxy	83.4	3.47	4.3	
UD S-glass/ Epoxy	71.0	3.54	6.5	
UD Graphite/ Polyimide ($V_f = 0.59$ –0.62)	–	–	5.8 ∼ 4.9	Off-axis tension test [Pindera and Herakovich (1986)]
UD Carbon/ Epoxy	98.0	–	–	Iosipescu shear test [Pierron and Vautrin (1997)]
UD Carbon/ Epoxy	78.0	2.30	–	Iosipescu shear test [Odegard and Kumosa (2000)]
Cross ply GFRP 45° off-axis	633.0	–	9.3	Iosipescu shear test [Khashaba (2004)]
UD Graphite/ Epoxy	80.7	–	4.9	Iosipescu shear test [Walrath and Adams (1983)]
UD Graphite/ Epoxy	68	–	–	Iosipescu shear test [Morton et al. (1992)
UD Carbon/ Epoxy	84	–	4.6	Iosipescu shear test [Zhou et al. (1995)

IPS properties of unidirectional (UD) composites. Pindera and Herakovich [7] suggested that 45 degree off-axis specimens are better for determination of IPS modulus. They also supported their findings through analytical studies. Ganesh and Naik [5] analyzed shear stress contribution to failure using the Tsai-Hill failure criterion in ±45 degree plain weave composite specimens. They recommended the use of ±45 degree off-axis balanced specimens to evaluate IPS behavior of plain weave fabric composites as shear contribution to failure was found to be 99%. Researchers have also used Iosipescu test specimens for determining IPS properties of composites [8–15]. Summary of the observations made on the IPS properties of composites subjected to quasi-static loading in the above studies is presented in Table 1.

Table 2
In-plane shear properties of composite materials under intermediate / high strain rate loading based on in-plane shear strain rate (from literature).

Material	Shear strain rate, (per sec)	Shear strength, (MPa)	Ultimate shear strain, (%)	Shear modulus, (GPa)	Reference
UD Graphite/ Epoxy	170	–	–	7.1	Daniel et al. (1981)
	140	–	–	10.1	
	160	–	–	7.8	
Woven Carbon/ Epoxy	1021	110	12 ∼ 15	–	Chiem and Liu (1998)
	2623	129		–	
	3631	139		–	
	5166	163		–	
	5410	173		–	
UD Glass/ Epoxy	0.0023	91	–	–	Tsai and Sun (2005)
	0.02	104	–	–	
	1.68	114	–	–	
	1016	137	–	–	
E-glass/ Epoxy (Cross-ply)	0.0024	40	3.87	4.3	Shokrieh and Omidi (2009)
	0.795	46.4	3.20	4.0	
	7.55	49.4	3.04	3.8	
	64.5	52.5	3.31	3.8	
	130.95	54.8	3.71	3.7	

Table 3
In-plane shear properties of composite materials under high strain rate loading based on axial strain rate (from literature).

Material	Axial strain rate, (per sec)	Shear strength, (MPa)	Ultimate shear strain, (%)	Shear modulus, (GPa)	Reference
90% UD E-glass/ Phenolic	10^{-4}	25.6	–	3.2	Barre et al. (1996)
	3×10^{-2}	22.2	–	2.4	
	3	31.5	–	1.4	
(+45/−45) E-glass/ Phenolic	10^{-4}	–	–	2.6	
	3×10^{-2}	–	–	2.1	
	4×10^{-1}	–	–	2.6	
UD Carbon/ Carbon ($V_f = 0.6$)	10^{-3}	16.7	–	–	Ishiguro et al. (1999)
	10^{-2}	17.1	–	–	
	0.1	17.6	–	–	
	1	18.0	–	–	
	5	18.3	–	–	
UD Carbon/ Epoxy	Quasi-static	127.1	8.00	–	Hsiao et al. (1999)
	0.1	151.2	6.97	–	
	6	160.2	4.96	–	
	300	190.2	6.29	–	
	1200	199.5	3.79	–	
E glass/poly propylene woven fabric	Quasi static	30.5	–	1.8	Kevi et al. (2010)
	33	14.1	–	0.3	
	70	25.1	–	0.5	
	91	24.1	–	0.2	

Liang et al [16] carried out experiments with ±45 degree UD carbon fiber reinforced and carbon fabric reinforced composite specimens on a universal testing machine (UTM). They studied in-plane properties such as shear modulus, shear strength, damage mechanisms and failure modes. They concluded that the fabric reinforced composite showed more ductile-like response in the pre-yield phase, and better load bearing ability in the post-yield phase compared to UD fiber reinforced composite.

Efforts have also been made for dynamic IPS characterization of composite materials. Daniel et al. [17] evaluated shear properties with the help of a drop test. They reported 30% increase in IPS strength and modulus values as compared to the corresponding quasi-static values. Chiem and Liu [18] used torsional split Hopkinson bar (TSHB) apparatus to investigate the dynamic behavior of woven carbon/epoxy composites under shear impact loading in the orthogonal direction. Barre et al. [19] studied strain rate dependency of IPS modulus using drop weight test apparatus. Al-Salehi et al. [20] characterized shear properties using burst tests on glass/epoxy and Kevlar/epoxy filament wound tubes. Al-Hassani and Kaddour [1] reviewed the work conducted by different authors on IPS behavior of composites under high strain rate loading up to 1998. Ishiguro et al. [21] investigated strain rate dependence of shear strength using UTM on double notched specimens. Hsiao et al. [22] evaluated IPS behavior using an off-axis technique on SHPB apparatus. Papadakis et al. [23] carried out tension tests at different crosshead displacement rates. They determined IPS properties from tension test results and analyzed the strain rate effect on these properties.