Crashworthiness of Various Random Chopped Carbon Fiber Reinforced Epoxy Composite Materials and Their Strain Rate Dependence

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Received 29 August 2005; accepted 5 January 2006
DOI 10.1002/app.24224
Published online 4 May 2006 in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: The ACC (Automotive Composite Consortium) is interested in investigating the use of random chopped fiber reinforced composites as crash energy absorbers primarily because of the low costs involved in their manufacture thus making them cost effective for automotive applications. Although many scientists have investigated the energy absorption characteristics in various continuous fiber reinforced composite materials and their dependence on strain rate, there is very little literature available on the energy absorption and crushing characteristics of random chopped fiber reinforced composite materials and their strain rate dependence. Therefore, the primary goal was to determine the crashworthiness of various random chopped carbon fiber composite material systems. To meet this goal, first an experimental set up was developed for discerning the deformation behavior and damage mechanisms that occur during the progressive crushing of composite materials. The three different random chopped carbon reinforced epoxy composite material systems studied were P4, HexMC, and CCS100. Quasi-static progressive crush tests were then performed on these random chopped carbon fiber composite plates to determine their crashworthiness. In addition, an attempt was made to investigate and characterize the strain rate effects on the energy absorption of a random chopped carbon fiber P4 composite. The specific energy absorption was found to increase with increasing loading rate from 15.2 to 762 cm/min. © 2006 Wiley Periodicals, Inc. J Appl Polym Sci 101: 1477–1486, 2006

Key words: strain rate; crashworthiness; energy absorption; composite materials; crush testing; plates; chopped fiber; carbon; epoxy P4

INTRODUCTION

Current legislation for automobiles requires that vehicles be designed such that in the event of an impact at speeds up to 15.5 m/s (35 mph) with a solid, immovable object, the occupants of the passenger compartment should not experience a resulting force that produces a net deceleration greater than 20 g. Crashworthy structures should be designed to absorb impact energy in a controlled manner, thereby bringing the passenger compartment to rest without the occupant being subjected to high decelerations, which can cause serious internal injury, particularly brain damage. In passenger vehicles the ability to absorb impact energy and be survivable for the occupant is called the "crashworthiness" of the structure. This absorption of energy is through controlled failure mechanisms and modes that enable the maintenance of a gradual decay in the load profile.

The crashworthiness of a material is expressed in terms of its specific energy absorption (SEA) which is characteristic to that particular material. It is defined as the energy absorbed per unit mass of a crushed

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Contract grant sponsor: Lightweight Materials Program, Office of Transportation Technologies, Assistant Secretary for Energy Efficiency and Renewable Energy, U.S. Department of Energy with UT-Battelle, LLC; contract grant number: DE-AC05–00OR22725.

Contract grant sponsor: Automotive Composites Consortium Energy Management Group.

Journal of Applied Polymer Science, Vol. 101, 1477–1486 (2006)

TABLE I
Summary of Published Data on the Effects of Loading Rate on Energy Absorption of Various Continuous Fiber-Reinforced Composite Materials

Authors	Materials studied	Observations
Bannerman and Kindervater[1]	Carbon/epoxy and Kevlar/epoxy	Energy absorption increased with crushing speed
Thornton[2–4]	Graphite/epoxy, Kevlar/epoxy, glass/epoxy, glass/polyester, and glass/vinylester	Very little change in specific energy absorption with crushing speed for graphite, Kevlar, and glass epoxy composites. 10% decrease and 20% increase in energy absorption with increasing testing speed for glass/vinylester and glass/polyester composites, respectively
Price and Hull[5]	Continuous strand mat-reinforced polyester resin tubes	Energy absorption decreased with increasing crushing speed
Farley[6,7]	Kevlar/epoxy, glass/epoxy, and carbon/epoxy	Energy absorption was independent of crushing speed for all three composite tubes with fiber architecture $[0 \pm \theta]_4$. Increase in energy absorption with crushing speed for carbon and Kevlar epoxy composite tubes with $[\pm\theta]_3$
Mamalis et al.[8]	Glass/vinylester and glass/polyester	Energy absorption decreased with increase in crushing speed for the circular conical specimen but remained constant for the thin-walled circular and square tube composites with increasing crushing speeds
Mamalis et al.[9,10]	Glass/vinylester	Energy absorption increased with increasing crushing speed
Berry and Hull[11]	Graphite/epoxy and glass/epoxy	Energy absorption increased with increasing crushing speed
Kindervater[12,13]	Carbon/epoxy, polyethylene/epoxy, carbon/polyamid, and Kevlar/epoxy	Decrease in energy absorption with increasing crushing speed for the carbon/epoxy tube. Energy absorption increased with increasing crushing speed for the polyethylene/epoxy and carbon/polyamid tubes. Very little change in energy absorption with crushing speed for Kevlar/epoxy composites
Keal[14]	Glass/polyester and glass/epoxy	Energy absorption decreased with increasing crushing speed.
Schmueser and Wickliffe[15]	Carbon/epoxy, Kevlar/epoxy, and glass/epoxy	Energy absorption decreased with increasing crushing speed
Ramakrishna and coworkers[16,17]	Carbon/epoxy and glass/epoxy	Energy absorption decreased with increasing crushing speed
Hamada and Ramakrishna[18]	Carbon/PEEK	Energy absorption decreased with increasing crushing speed
Hull[19–21]	Glass/polyester, glass/epoxy, carbon/epoxy, and Kevlar/epoxy	Energy absorption was rate independent
Lavoie et al.[22,23]	Graphite/PEEK, graphite/epoxy, and hybrid graphite–Kevlar/epoxy	Energy absorption decreased with increasing crushing speed

material. Mathematically SEA = $W/(V_\rho)$, where the total energy absorbed, W, is calculated by integrating the area under the load-deflection curve; V is the volume of crushed material; and ρ is the density of the material.

Vehicle size and mass provide a certain degree of protection but can have negative inertial effects. Driven by the need to overcome these negative effects of both size and mass coupled with mandates for increased fuel efficiency, an attempt is being made to use composites in the development of energy dissipating devices. The ability to tailor composites, in addition to their attributes of high stiffness-to-weight and strength-to-weight ratios, fatigue resistance and corrosion resistance, makes them very attractive in crashworthiness. The challenge is the use of specific features of geometry and materials in enabling greater safety while simultaneously decreasing the weight, without negatively affecting the overall economics of fabrication and production.

To reduce the overall weight and improve the fuel economy of vehicles, more and more metal parts are being replaced by polymer composite materials. Contrary to metals, especially in compression, most composites are generally characterized by a brittle rather than ductile response to load. While metal structures

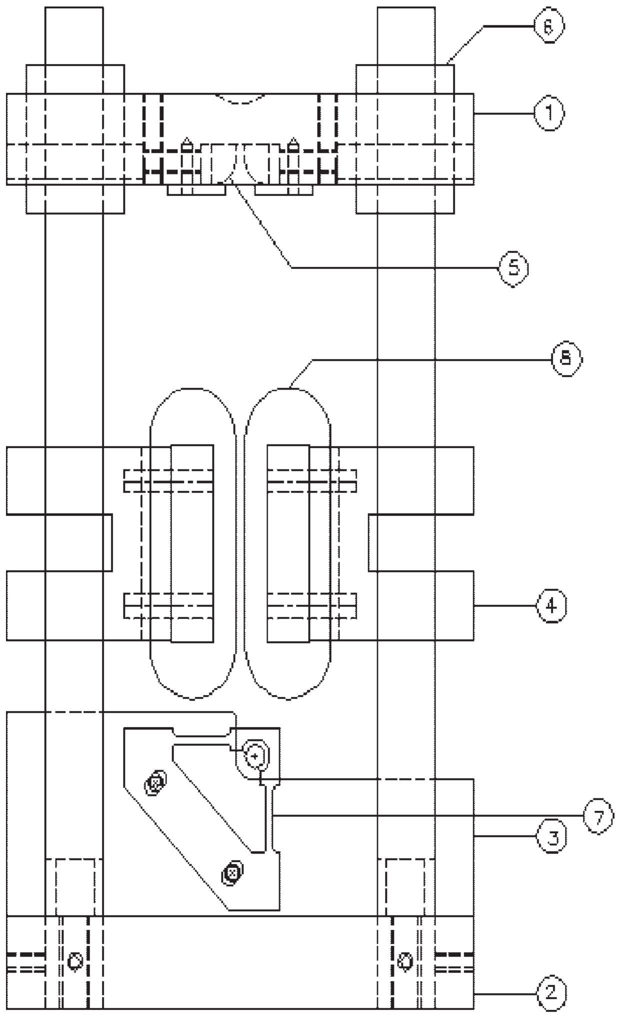

Figure 1 Schematic of test fixture design. Primary components of the fixture are as follows: (1) top plate; (2) base plate; (3) profile block; (4) roller plate; (5) grip plate and insert; (6) linear shaft and bearing; (7) load cell; (8) roller way.

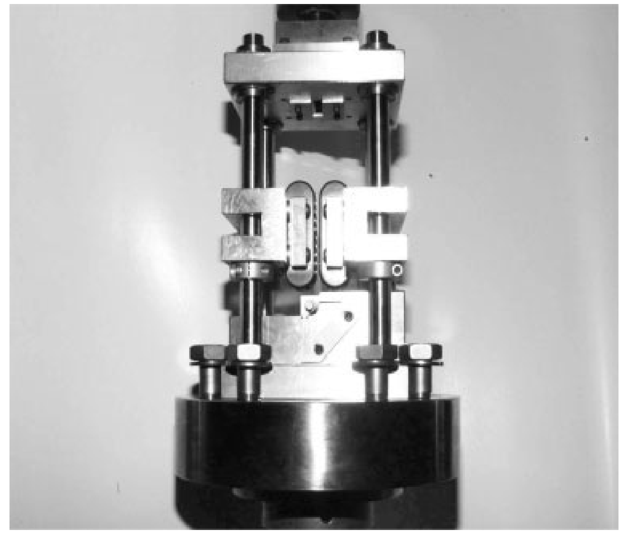

Figure 2 Test fixture assembly.

collapse under crush or impact by buckling and/or folding in accordion (concertina) type fashion involving extensive plastic deformation, composites fail through a sequence of fracture mechanisms involving fiber fracture, matrix crazing and cracking, fiber-matrix debonding, delamination, and interply separation. The actual mechanisms and sequence of damage are highly dependent on the geometry of the structure, lamina orientation, type of trigger, and crush speed, all of which can be suitably designed to develop high energy absorbing mechanisms.

The ACC (Automotive Composite Consortium) is interested in investigating the use of random chopped fiber reinforced composites as crash energy absorbers primarily because of the low costs involved in their manufacture thus making them cost effective for automotive applications. Although many scientists have investigated the energy absorption characteristics in various continuous fiber reinforced composite materials, there is very little literature available on the energy absorption and crushing characteristics of random chopped fiber reinforced composite materials. Therefore the energy absorption in various random chopped carbon fiber composite material systems has been quantified in this manuscript. The effect of loading rate on the energy absorption characteristics in various continuous fiber reinforced composite materials have also been investigated in the past. Table I summarizes the data published on the effects of loading rate on energy absorption characteristics of various continuous fiber reinforced composite materials. But there is no literature available on the effect of loading rate on the energy absorption of random chopped fiber reinforced composite materials. Therefore the strain rate dependence of a random chopped carbon/epoxy P4 composite has also been investigated in this manuscript.

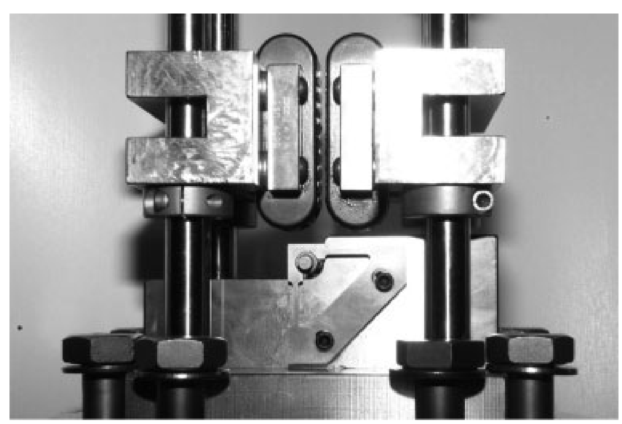

Figure 3 Roller ways and contact profile constraint.

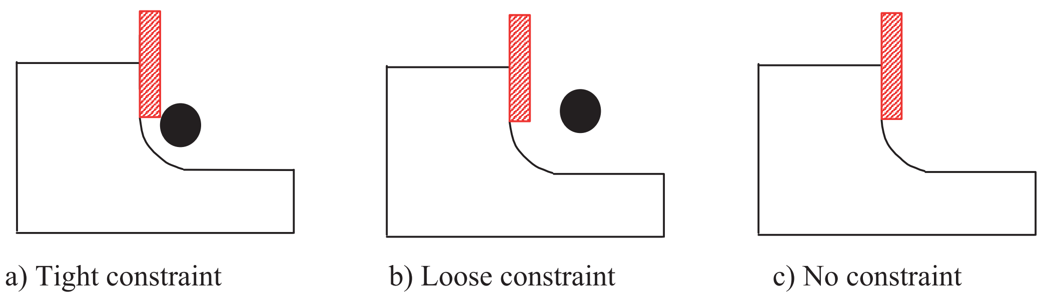

Figure 4 Constraint conditions. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

Practical considerations related to the cost of production of the test specimens were of paramount importance in developing the test methodology. Composite plate specimens are very cheap to fabricate, and it has been observed that plate specimens progressively crush in modes very similar to the damage modes that occur during progressive crushing of composite tubes. Also plates can be easily produced with consistently high quality.

EXPERIMENTAL

Test method

A test fixture design was developed for determining the deformation behavior and damage mechanisms that occur during progressive crushing of composite materials. The fixture was designed to isolate damage modes associated with frond formation (splaying mode) in composite tubes by testing plate geometries. The design of the test fixture can accommodate different plate widths (up to a maximum of 50 mm), plate thicknesses (3 ± 1.5 mm), contact profile shapes (profile block radius: 6.4 mm and 13 mm), and contact profile constraints (tight, loose and no constraint) as shown in Figures 1–4.

Features incorporated into the design include an observable crush zone, long crush length (50 mm), interchangeable contact profile, frictionless roller for contact constraint, and out of plane roller supports to prevent buckling (Fig. 3). The brackets on each side of the profile plate were designed to provide a method of constraining the specimen to deform along the path of the contact profile (Fig. 4). The severity of the contact profile constraint was determined by the position of the brackets and was adjustable using slotted positioning holes. The objective of the profile constraint was to determine if different damage mechanisms could be activated depending on the position of the roller. Jacob and coworkers[24] provide more details of the fixture design and its validation.

Material system investigated

Through ongoing research programs a considerable amount of experimental data related to the energy absorption characteristics of polymer composite materials have been generated. For this class of materials, the energy absorption is dependent on many parameters including fiber type, matrix type, fiber architecture, specimen geometry, processing conditions, fiber volume fraction, and impact velocity. Changes in these parameters can cause subsequent changes in their SEA up to a factor of 2. Composite materials are recognized as being efficient energy absorbers; however, for a material to be suitable for automotive crashworthy structural applications they must also have low raw material and manufacturing costs. The use of random chopped carbon fiber and compression

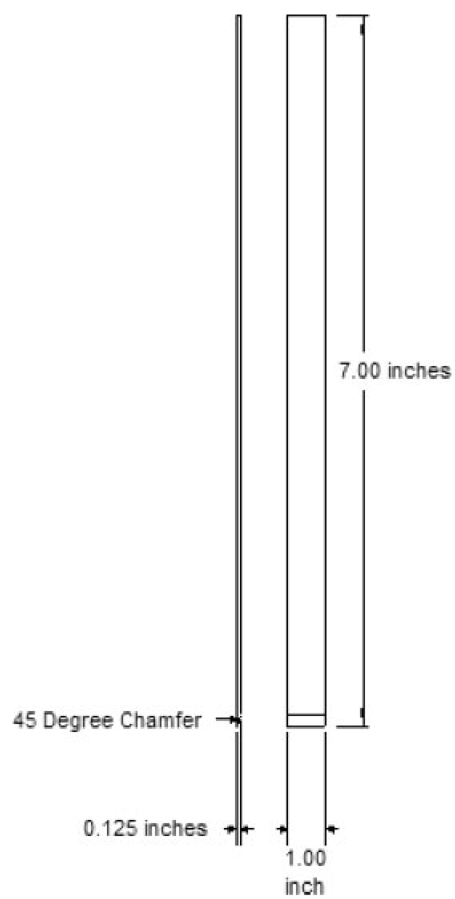

Figure 5 Chamfered specimen configuration.

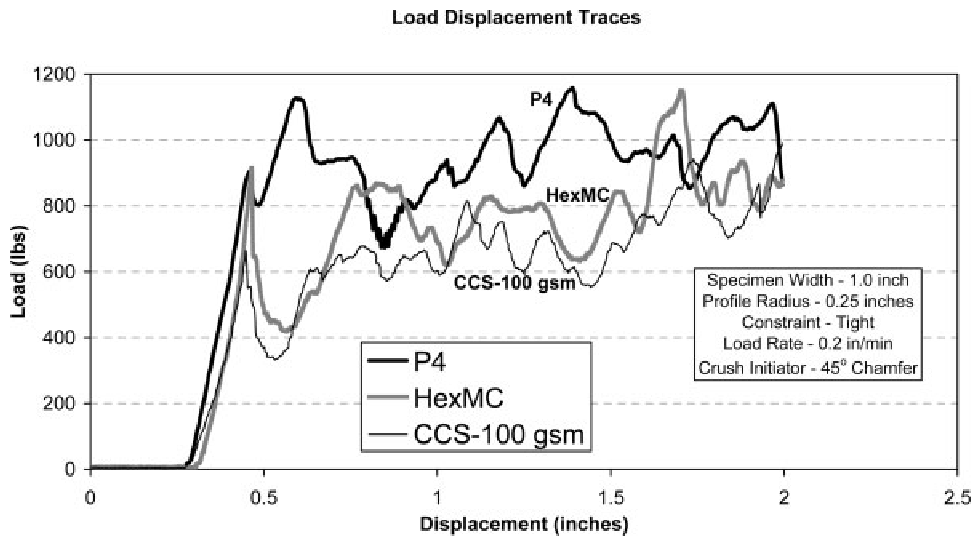

Figure 6 Load displacement traces for the various random chopped fiber reinforced composites.

molded processing methods has the potential to satisfy these criteria. Hence, the ACC (Automotive Composite Consortium) was interested in investigating the use of carbon fibers in chopped fiber reinforced composite materials. Carbon fiber reinforced tubes display higher SEA than other fiber-reinforced tubes. This is a direct result of the lower density of the carbon fiber thus also contributing to the lightweight of the structures they are used in. Epoxy, which is regarded as a standard resin that frequently finds use in most composites, was chosen as the matrix.

The CCS100 composite plates were manufactured from Toray T700 chopped carbon fiber with YLA RS-35 epoxy resin using compression molding techniques. While YLA Incorporated (Benicia, CA) supplied the molding compound, CCS Composites LLC (Benicia, CA) compression molded the plates. The CCS100 composites had a fiber volume fraction of 50% and a fiber length of 25.4 mm (1 in.). The random chopped carbon fiber epoxy resin HexMC composite plates, which had a fiber volume fraction of 57% and 50.8 mm (2 in.) fiber length, were compression molded by Hexcel Composites LLC. The compression molded P4 composite plates were manufactured from chopped carbon fiber having 50.8 mm (2 in.) fiber length and 36% fiber volume fraction with Hetron epoxy resin.

Testing procedure

The P4, CCS-100, and HexMC plate specimen plates had a nominal length of 178 mm (7 in.) and a width of 25.4 mm (1 in.). A 45° chamfer was used as the crush initiator (Fig. 5). A diamond cut-off wheel was used to cut the specimens off the composite panel. No coolant was used during cutting to prevent contamination of the test specimens. The above three random chopped carbon reinforced epoxy composite material systems were tested using a servo-hydraulic test machine at a loading rate of 0.5 cm/min (0.2 in./min). However, the P4 composite material system was tested at additional loading rates of 15.2 cm/min (6 in./min) and 762 cm/min (300 in./min), to investigate their strain rate dependence. An MTS model 407 controller, which is a single channel, digitally-supervised proportional, integral, derivative, feed forward (PIDF) servo controller, was used to provide complete control of one servo hydraulic channel/station in the MTS testing system. The load-deflection response was recorded using a computerized data acquisition system. The area under the load deflection curve was calculated for the total energy absorbed, and the initial peak load, maximum peak load and sustained crush load were identified.

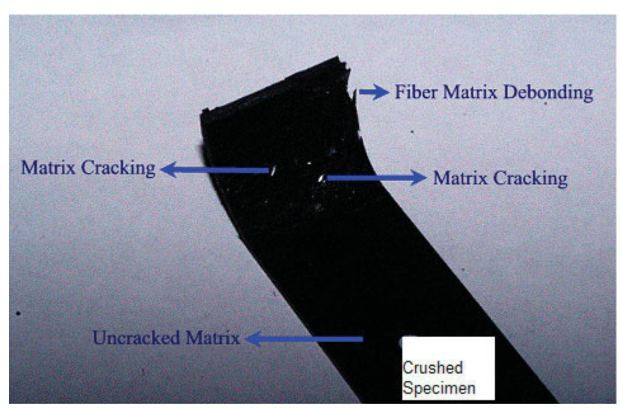

Figure 7 Matrix cracking. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

TABLE II
Experimental Data from Tests Conducted with a Profile Block of Radius 0.635 cm at 0.5 cm/min Loading Rate on P4

Spec. number	Spec. width (cm)	Profile radius (cm)	Constraint	Load rate (cm/min)	Initial peak load (N)	Max. peak load (N)	Sustained crush load (N)	SEA (J/g)	Average SEA (J/g)
ENABS0 2P41	2.551	0.635	Tight	0.5	2342.7	4696.2	3136.3	30.76	
ENABS0 2P42	2.556	0.635	Tight	0.5	2536.7	5515.4	3429.2	34.53	
ENABS0 2P43	2.555	0.635	Tight	0.5	2987.0	4830.5	3642.6	36.77	
ENABS0 2P44	2.550	0.635	Tight	0.5	2592.3	4787.1	3592.1	36.71	
ENABS0 2P45	2.551	0.635	Tight	0.5	3156.6	4475.1	333.2	33.91	
ENABS0 2P46	2.549	0.635	Tight	0.5	2860.9	4560.6	3503.2	35.55	
ENABS0 2P47	2.550	0.635	Tight	0.5	4016.6	5147.9	3997.7	40.19	
ENABS0 2P48	2.560	0.635	Tight	0.5	2734.7	5038.1	3937.2	39.30	
ENABS0 2P49	2.558	0.635	Tight	0.5	3063.0	5317.5	3873.1	38.50	
ENABS0 2P410	2.545	0.635	Tight	0.5	3522.8	5131.7	3848.6	38.52	36.47

RESULTS AND DISCUSSION

All the P4, HexMC, and CCS100 specimens tested generated load deflection curves that were similar to the ones generated during the progressive crushing of composite tubes. Figure 6 shows the load displacement traces of the P4, HexMC, and CCS100 composite plate specimens. It had four stages, the first one being characterized by an initial rapid load increase. A rapid load drop occurred in the second stage of the load deflection curve followed by a gradual saturation of the load. The final stage was characterized by stable crushing at a constant mean load. The small load fluctuations and serrations in the fourth stage of the curve are characteristic of stable crushing. For all P4, HexMC, and CCS100 specimens tested, local crushing took place at the chamfered end of the plates. Matrix cracking occurred at the ends of the fiber tows because of stress concentration at these ends. Figure 7 illustrates the matrix cracking occurring at the ends of fiber tows. Fiber-matrix debonding also took place in a majority of the specimens that were tested.

On comparing the performance of the P4, HexMC and CCS100 composite plates, the SEA of P4 composites was found to be greater than that of the HexMC and CCS100 composites. Tables II–IV and Figure 8 show comparison of the specific energy absorbed by the P4, HexMC, and CCS100 composites. The P4 composites with a fiber volume fraction of 36% had the highest SEA when compared with that of the HexMC and CCS100 composites, which had higher fiber volume fractions. Therefore, it can be concluded that decreased fiber volume fraction caused an increase in SEA of random chopped carbon fiber composites. This is in agreement with a previous study conducted by Starbuck et al. on random chopped fiber composites where in the same observation was reported.[25]

It is not always true, as one would normally think, that an increase in the fiber content would necessarily improve the SEA capability of a composite material. A possible explanation for the above statement is that as the fiber volume fraction increases, the volume of the matrix between the fibers decrease. This causes an increase in the matrix density. This further leads to a decrease in the interlaminar strength of the composite. As interlaminar strength decreases, interlaminar cracks form at lower loads, resulting in a reduction in the energy absorption capability.

TABLE III
Experimental Data from Tests Conducted with a Profile Block of Radius 0.635 cm at 0.5 cm/min Loading Rate on HexMC

Spec. number	Spec. width (cm)	Profile radius (cm)	Constraint	Load rate (cm/min)	Initial peak load (N)	Max. peak load (N)	Sustained crush load (N)	SEA (J/g)	Average SEA (J/g)
ENABSHEXMC1	2.542	0.635	Tight	0.5	5191.4	5191.4	3714.8	37.39	
ENABSHEXMC2	2.539	0.635	Tight	0.5	3233.9	4884.8	3132.4	31.52	
ENABSHEXMC3	2.541	0.635	Tight	0.5	4061.4	5115.4	3203.0	32.41	
ENABSHEXMC4	2.547	0.635	Tight	0.5	4188.9	4605.3	2972.5	30.05	
ENABSHEXMC5	2.540	0.635	Tight	0.5	4038.3	4298.8	2852.8	29.42	
ENABSHEXMC6	2.539	0.635	Tight	0.5	6334.9	6334.9	3738.0	37.63	
ENABSHEXMC7	2.541	0.635	Tight	0.5	3635.4	3923.0	2798.3	28.35	
ENABSHEXMC8	2.544	0.635	Tight	0.5	3748.0	4658.2	3506.4	35.55	
ENABSHEXMC9	2.541	0.635	Tight	0.5	4898.3	5248.3	3912.9	39.64	
ENABSHEXMC10	2.542	0.635	Tight	0.5	4007.1	4007.1	2975.0	29.82	33.18

TABLE IV
Experimental Data from Tests Conducted with a Profile Block of Radius 0.635 cm at 0.5 cm/min Loading Rate on CCS-100

Spec. number	Spec. width (cm)	Profile radius (cm)	Constraint	Load rate (cm/min)	Initial peak load (N)	Max. peak load (N)	Sustained crush load (N)	SEA (J/g)	Average SEA (J/g)
ENABS0 2CCF1001	2.540	0.635	Tight	0.5	3815.9	4174.0	3035.3	30.95	
ENABS0 2CCF1002	2.538	0.635	Tight	0.5	3799.6	4873.9	2865.8	28.96	
ENABS0 2CCF1003	2.538	0.635	Tight	0.5	3765.7	4799.3	3106.9	31.10	
ENABS0 2CCF1004	2.555	0.635	Tight	0.5	3423.8	5803.1	3442.4	34.36	
ENABS0 2CCF1005	2.550	0.635	Tight	0.5	2940.9	4395.1	2789.0	27.95	
ENABS0 2CCF1006	2.538	0.635	Tight	0.5	2920.6	4054.6	3024.4	30.49	
ENABS0 2CCF1007	2.536	0.635	Tight	0.5	3090.1	5729.9	3473.9	34.87	
ENABS0 2CCF1008	2.536	0.635	Tight	0.5	3687.0	5525.1	3449.1	34.75	
ENABS0 2CCF1009	2.543	0.635	Tight	0.5	2534.0	4176.1	2402.7	25.26	
ENABS0 2CCF10010	2.538	0.635	Tight	0.5	2801.2	4568.7	3127.2	32.89	31.16

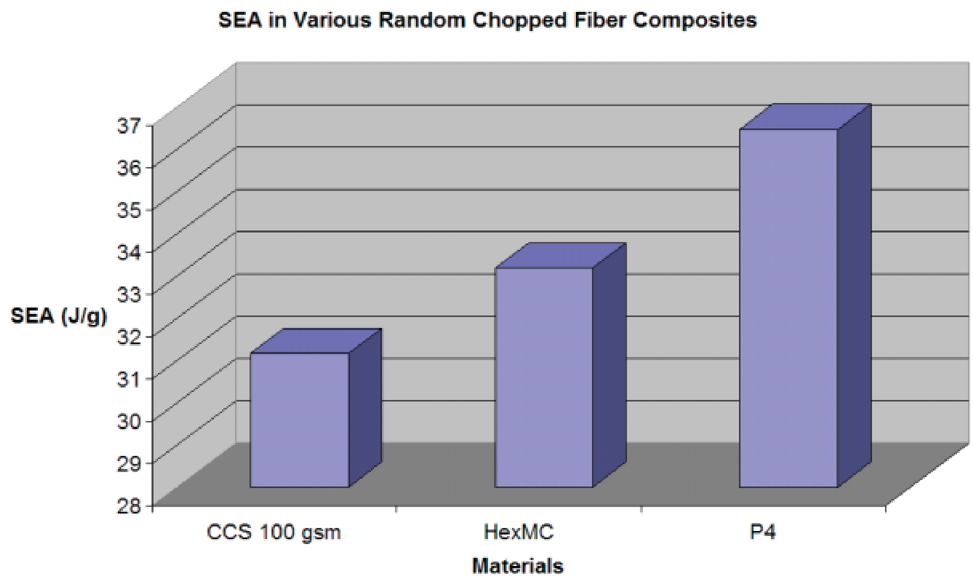

Figure 8 Specific energy absorption (SEA) in CCS 100, HexMC, and P4 Composites. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

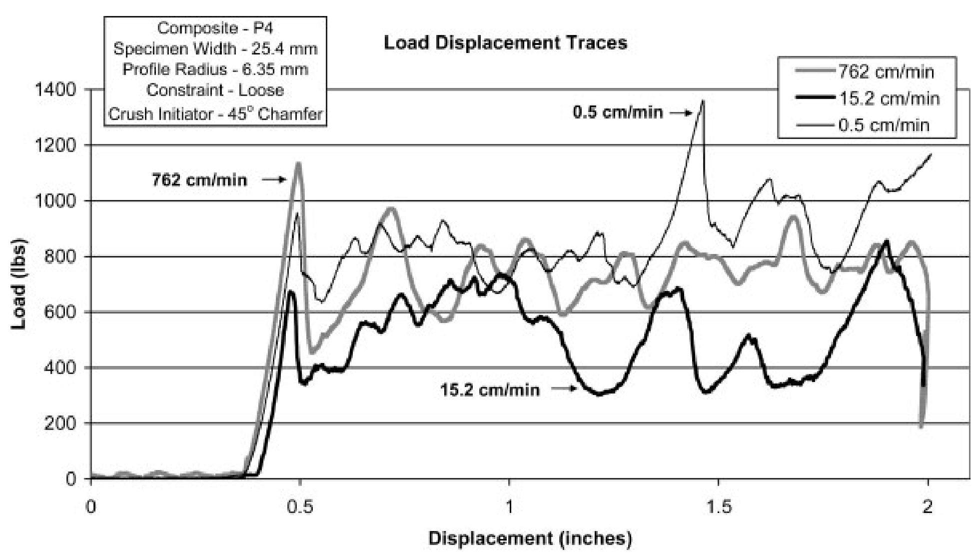

Figure 9 Load displacement traces for a test conducted on P4 in the loose constraint condition at loading rates of 0.5, 15.2, and 762 cm/min, respectively.

TABLE V
Experimental Data from Tests Conducted with a Profile Block of Radius 0.635 cm at 15.2 cm/min Loading Rate on P4

Spec. number	Spec. width (cm)	Profile radius (cm)	Constraint	Load rate (cm/min)	Initial peak load (N)	Max. peak load (N)	Sustained crush load (N)	SEA (J/g)	Average SEA (J/g)
ENABS0 2P412	2.543	0.635	Loose	15.2	3020.2	4247.8	2009.5	20.12	
ENABS0 2P413	2.545	0.635	Loose	15.2	3576.2	4283.4	2534.6	25.42	
ENABS0 2P414	2.542	0.635	Loose	15.2	2686.6	3469.4	1905.2	19.24	
ENABS0 2P415	2.542	0.635	Loose	15.2	3429.4	3460.5	1699.4	17.13	
ENABS0 2P416	2.546	0.635	Loose	15.2	3215.9	3215.9	2081.0	20.99	
ENABS0 2P417	2.543	0.635	Loose	15.2	3367.1	4269.8	2361.4	22.75	
ENABS0 2P418	2.545	0.635	Loose	15.2	3233.7	3545.1	2229.1	21.81	
ENABS0 2P419	2.546	0.635	Loose	15.2	2998.0	3798.6	2228.2	21.82	
ENABS0 2P420	2.542	0.635	Loose	15.2	3687.4	3896.5	2279.1	22.42	21.30[a]

[a] SD, 2.35; CV, 11.00.

The CCS100 composite plates, which had a fiber length for 1 in., recorded the lowest SEA when compared with the P4 and HexMC composites, which had a fiber length of 2 in. Therefore, it can be concluded that an increase in fiber length caused a decrease in the SEA for random chopped carbon fiber composite materials. This is in agreement with a previous study on the effect of fiber length on the energy absorption capabilities of composites that reported an increase in the SEA with increased fiber lengths.[26] However, the previous work done by Jacob et al. on random chopped carbon fiber composites with 1 and 2 in. fiber lengths found that greater fiber lengths caused decreased SEA.[27] Hence there seems to be a lack of consensus about the influence of fiber length on the energy absorption in random chopped fiber composite materials. Hence more work needs to be done in pursuit of the above goal wherein chopped carbon composites with varying fiber lengths but with other parameters identical to each other need to be investigated.

The SEA of the 3 random chopped carbon fiber composite material systems (P4, HexMC and CCS100) was higher when compared with that of other fiber resin systems investigated by Jacob et al. like graphite/epoxy crossply laminates (CP No. 1 (25.58 J/g) and CP No. 2 (17.62 J/g)),[28] a graphite/epoxy braided material system (17.23 J/g)[28] and a glass-reinforced continuous strand mat (25.58 J/g).[29] The above results are very encouraging for the use of random chopped fiber reinforced composites as crash energy absorbers and as desired by the ACC because of the low costs involved in their manufacture, thus making them cost effective for automotive applications.

For the P4 composite plate specimens tested at higher loading rates, the failure mechanisms observed (local crushing, matrix cracking, and fiber matrix debonding) were similar to that seen at the quasi-static rate (0.5 cm/min). However, it was observed that the matrix cracking at the fiber tow ends and the fiber matrix debonding was more in the P4 composite plate specimens tested at 0.5 cm/min than what took place at higher rates.

All the P4 specimens tested at higher rates generated load deflection curves that were similar to the ones generated during the progressive crushing of composite tubes. Figure 9 shows the load displacement traces of the P4 composite plate specimens tested at 3 different loading rates. It had the same four stages as observed for the P4, HexMC, and CCS100 compos-

TABLE VI
Experimental Data from Tests Conducted with a Profile Block of Radius 0.635 cm at 762 cm/min Loading Rate on P4

Spec. Number	Spec. width (cm)	Profile radius (cm)	Constraint	Load rate (cm/min)	Initial peak load (N)	Max. peak load (N)	Sustained crush load (N)	SEA (J/g)	Average SEA (J/g)
ENABS0 2P421	2.547	0.635	Loose	762	5337.6	5604.5	3705.6	36.34	
ENABS0 2P424	2.545	0.635	Loose	762	5026.2	5026.2	3112.5	30.06	
ENABS0 2P425	2.547	0.635	Loose	762	4301.2	5604.5	3161.8	30.16	
ENABS0 2P426	2.547	0.635	Loose	762	5159.7	5159.7	3216.5	31.23	
ENABS0 2P427	2.550	0.635	Loose	762	4336.8	5426.6	2845.2	27.40	
ENABS0 2P428	2.548	0.635	Loose	762	4581.4	4803.8	3254.9	30.91	
ENABS0 2P429	2.547	0.635	Loose	762	5204.2	5871.4	3079.1	29.11	
ENABS0 2P430	2.547	0.635	Loose	762	5159.7	5159.7	3251.8	30.66	30.73

[a] SD, 2.57; CV, 8.36.

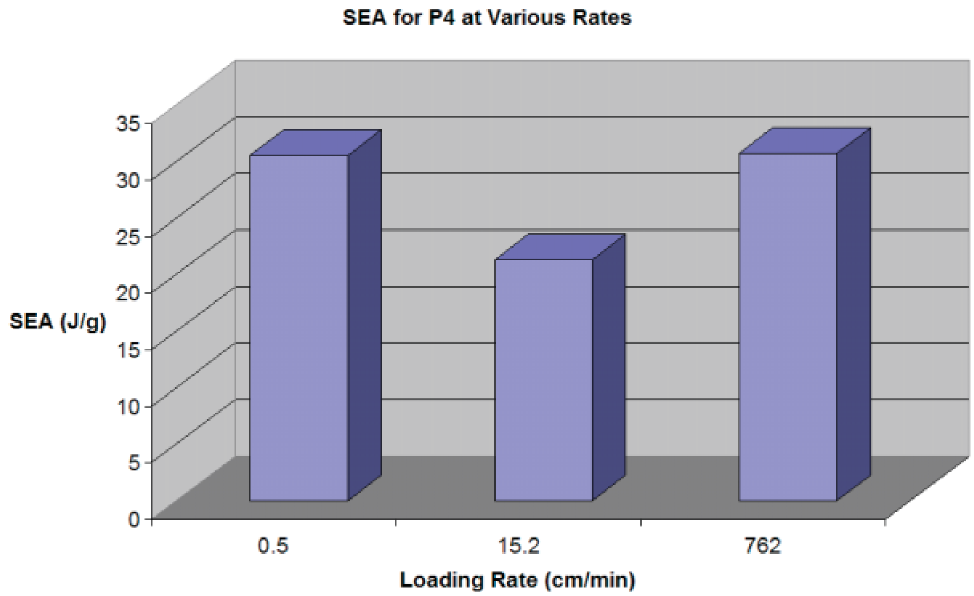

Figure 10 Specific energy absorption (SEA) in P4 composites at loading rates of 0.5, 15.2, and 762 cm/min respectively. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

ites when tested at quasi-static rates that have been previously described in the manuscript.

On loading the P4 composite plate specimens at higher rates of 15.2 and 762 cm/min respectively, the SEA of P4 composite at 762 cm/min was found to be greater than the SEA at 15.2 cm/min. Tables II, V, and VI and Figure 10 show a comparison of the specific energy absorbed by the P4 composites at loading rates of 0.5, 15.2, and 762 cm/min. The increase in SEA with increase in loading rate from 15.2 to 762 cm/min is because of the increased fracture toughness of the P4 composite with increasing loading rate as observed by Jacob et al. during a previous study.[30] For brittle fiber resin composites like the carbon/epoxy P4 composite an increase in loading rate causes an increase in the fracture toughness of the composite because of the increased fracture toughness of the epoxy matrix resin in the composite with increasing loading rate. Increased fracture toughness of the composite with increasing loading rate means more resistance to crack formation. Therefore, there is more energy absorption in the composite at higher loading rates. The high SEA in the P4 composite plates loaded at 0.5 cm/min is due to greater matrix cracking at the fiber tow ends and fiber matrix debonding which contributed to the greater energy being absorbed.

CONCLUSIONS

Although many scientists have investigated the energy absorption characteristics in various continuous fiber reinforced composite materials, there is very little literature available on the energy absorption and crushing characteristics of random chopped fiber reinforced composite materials. To identify and quantify the energy absorbing mechanisms in candidate automotive composite materials, test methodologies were developed for conducting progressive crush tests on composite specimens that have simplified geometries. Quasi-static progressive crush tests were performed on three different random chopped carbon fiber composite material systems (P4, HexMC, and CCS100) to determine their crashworthiness. All the three random chopped fiber composite systems recorded superior SEA thus demonstrating their use as crash energy absorbers as desired by the ACC, because of the low costs involved in their manufacture thus making them cost effective for automotive applications. There is no literature available on the effect of loading rate on the energy absorption of random chopped fiber reinforced composite materials. Hence progressive crush strip tests were conducted on the randomly oriented chopped carbon fiber P4 composite material at higher loading rates to evaluate the strain rate dependence of their energy absorption capability. The SEA of the P4 composites was found to increase with increasing loading rate. Explanations for all the observed trends and results have been detailed in the manuscript. Further studies on the strain rate effects on the crashworthiness of random chopped fiber composites are suggested where in the composites are loaded at even higher rates than reported in this manuscript. The experimental data in conjunction with the test observations will be used to develop analytical models for predicting the crashworthiness of automotive composite structures.

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