Crashworthiness of Automotive Composite Material Systems

George C. Jacob,[1] John F. Fellers,[1] J. Michael Starbuck,[2] Srdan Simunovic

[1]*Materials Science and Engineering Department, University of Tennessee, Knoxville, 434 Dougherty Engineering, Knoxville, Tennessee 37996, USA*
[2]*Polymer Matrix Composites Group, Metals and Ceramics Division,* [3]*Computational Material Science, Computer Science and Mathematics Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-6359, USA*

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ABSTRACT: The energy absorption capability of a composite material is important in developing improved human safety in an automotive crash. In passenger vehicles, the ability to absorb impact energy and be survivable for the occupant is called the crashworthiness of the structure. The crashworthiness in terms of the specific energy absorption (SEA) of a chopped carbon fiber (CCF) composite material system was compared with that of other fiber resin systems such as graphite/epoxy cross-ply laminates (CP#1 and CP#2), a graphite/epoxy-braided material system (O), and a glass-reinforced continuous-strand mat (CSM). The quantity of these material systems needed to ensure passenger safety in a midsize car traveling at various velocities was calculated and compared. The SEA of the chopped carbon fiber composite material was the highest compared to that of all the other composites investigated. It was calculated that only 4.27 kg of it would need to be placed at specific places in the car to ensure passenger safety in the event of a crash at 15.5 m/s (35 mph). This clearly led to an important practical conclusion that only a reasonable amount of this composite material is required to meet the necessary impact performance standard. The CCF composite tested at 5 mm/min crushing speed met both the criteria that need to be satisfied before a material is deemed highly crashworthy: A high magnitude of energy absorption and a safe allowable rate of this energy absorption.© 2004 Wiley Periodicals, Inc. J Appl Polym Sci 92: 3218–3225, 2004

Key words: composites; fibers; resins

INTRODUCTION

In passenger vehicles, the ability to absorb impact energy and be survivable for the occupant is called the crashworthiness of the structure. The vehicle must 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, its occupants do not experience a resulting force that produces a net deceleration greater than 20 *g*. Subjection of the occupants to decelerations greater than 20 *g* can cause serious internal injury, particularly brain damage. The use of composite materials as energy absorbers is important in developing improved human safety in an automotive crash. Energy absorption in these composite materials is dependent on many parameters such as fiber type,[1–16] matrix type,[6,17–21] fiber architecture,[1,2,9,17,22–24] specimen geometry,[3,7,25–35] and fiber volume fraction.[2,22,36–39] Changes in these parameters can cause subsequent changes in the specific energy absorption (SEA) of composite materials up to a factor of 2.

Correspondence to: G. C. Jacob (gjacob@utk.edu).
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Through ongoing research programs, a considerable amount of experimental data on the energy absorption characteristics of polymer composite materials has been generated. They were found to be efficient energy absorbers and suitable for crashworthy structural applications. There are a lot of other criteria, however, in addition to a material being crashworthy, that need to be met before one can begin the use of a particular composite as a crash energy absorber in automobiles. Some of the primary criteria are low costs involved in their manufacture, the raw materials being readily available, and many more. Once a composite material is identified to meet the above necessary requirements, one ought to study the effect all the controllable parameters (such as fiber volume fraction, specimen geometry, etc.) will have on its energy absorption capabilities, in an attempt to design the most crashworthy structure.

The Automotive Composite Consortium (ACC) was interested in investigating the use of 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 chopped fiber-reinforced composite materials. Therefore, the primary goal was to determine the crashworthiness of a chopped carbon fiber composite material system and to see how it compared with that of other fiber resin systems such as graphite/epoxy cross-ply laminates, a graphite/epoxy-braided material system, and a glass-reinforced continuous strand mat. To meet this goal, first an experimental setup was developed for discerning the deformation behavior and damage mechanisms that occur during the progressive crushing of composite materials.[40] The composite material systems studied were chopped carbon fibers reinforced in an epoxy resin system (CCF),[41,42] graphite/epoxy cross-ply laminates (CP#1 and CP#2),[40] graphite/epoxy triaxial braids with $0/+30^o/-30^o$ fiber orientation (O),[40] and glass/polyurethane continuous strand mat (CSM).[43] Quasi-static progressive crush tests were then performed on these composite plates to identify and quantify their energy-absorbing mechanisms. An attempt was made to understand in great detail the effect of various material (fiber volume fraction, fiber length, fiber tow size)[42] and test (specimen width, loading rate, profile radius, constraint condition)[40,41,42,43] parameters on their energy absorption capability by varying these parameters during testing. The combination of fiber volume fraction, fiber length, fiber tow size, and specimen width[41,42] that yielded the highest energy absorbing material was identified. The 50-mm (2-in.)-wide CCF specimens belonging to a panel group having a fiber tow size of 150 grams per square meter (gsm), a fiber length of 1 in., and a 50% fiber volume fraction recorded the highest SEA, equal to 28.11 kJ/kg when tested at 5 mm/min crushing speed under the tight constraint condition using a profile block of radius 6.4 mm.[41,42] For details on the above-mentioned work, see refs 40–44.

In this article, the crashworthiness in terms of the SEA of chopped carbon fibers reinforced in an epoxy resin system was compared with that of other fiber resin systems such as graphite/epoxy cross-ply laminates, a graphite/epoxy-braided material system, and a glass-reinforced continuous strand mat. The quantity of these material systems needed to ensure passenger safety in a midsize car traveling at various velocities was calculated and compared. It was verified whether the CCF composite crushed at 5 mm/min loading rate met both the criteria that need to be satisfied before a material is deemed highly crashworthy: a high magnitude of energy absorption and a safe allowable rate of this energy absorption.

COMPARISON OF MATERIAL SYSTEMS INVESTIGATED

A new test fixture design was developed for determining the deformation behavior and damage mechanisms that occur during progressive crushing of composite plates.[40] Features incorporated into the design include an observable crush zone, long crush length (2 in.), interchangeable contact profile, frictionless roller for contact constraint, and out-of-plane roller supports to prevent buckling. See Figures 1 and 2 for photos of the test fixture. The composite plate specimen is clamped in the top plate by the grip inserts. The specimen is then loaded in compression and crushed through the contact profile as defined by the profile block via the top plate that is connected to the load train using a shaft coupler. The top plate is displaced downward, relative to the base plate and profile block. Alignment is maintained by using four linear shafts and linear bearings. Attached to the roller plates that are positioned on the linear shafts by shaft collars are the roller ways. The roller ways are used to reduce the unsupported length of the specimen, thereby preventing the specimen from buckling. The brackets on either side of the profile plate were designed to provide a method of constraining the specimen to deform along the path of the contact profile. The use of oil-impregnated bronze sleeve bearings in each bracket and the installation of a precision ground shaft that acts as a roller accomplish this. The severity of the contact profile constraint is determined by the position of the load cell brackets and is adjustable by using slotted positioning holes. See Figure 3. Slotted holes are used throughout the test fixture design to accommodate different plate thicknesses and maintain alignment with the centerline of the load train. Figures 4–6 depict crushed plate samples of graphite/epoxy cross-ply laminates (CP#1), glass-reinforced CSM, and CCF composites, respectively.

To identify the best material system among all the composites investigated, a comparison of the SEA recorded in all the tests conducted at a crushing speed of 5 mm/min on the 50-mm (2-in.)-wide specimens under the tight constraint condition by using a profile block having a radius of 6.4 mm was made. It was found that the SEA of the chopped carbon fiber composite material was the highest (28.11 Jg^{-1}),[41,42] followed by that of the CSM material (26.50 Jg^{-1}),[43] the CP#1 panel group (25.58 Jg^{-1}),[40] and the CP#2 panel group (17.62 Jg^{-1})[40] in the order of decreasing SEA. See Figure 7. The lower SEA in panel CP#2 is attributed to the weaker interfacial bond strength, resulting from poor consolidation, requiring less energy to delaminate. The higher SEA in the CCF materials is attributed to the low density of the carbon fibers and the large amount of energy absorbed because of the matrix cracking at the ends of the chopped carbon fiber tows because of stress concentration at these ends.

MATERIAL PERFORMANCE REQUIREMENTS

Consider a midsize car with a mass of 1000 kg (2200 lb) traveling at a velocity of 15.5 m/s (35 mph). The

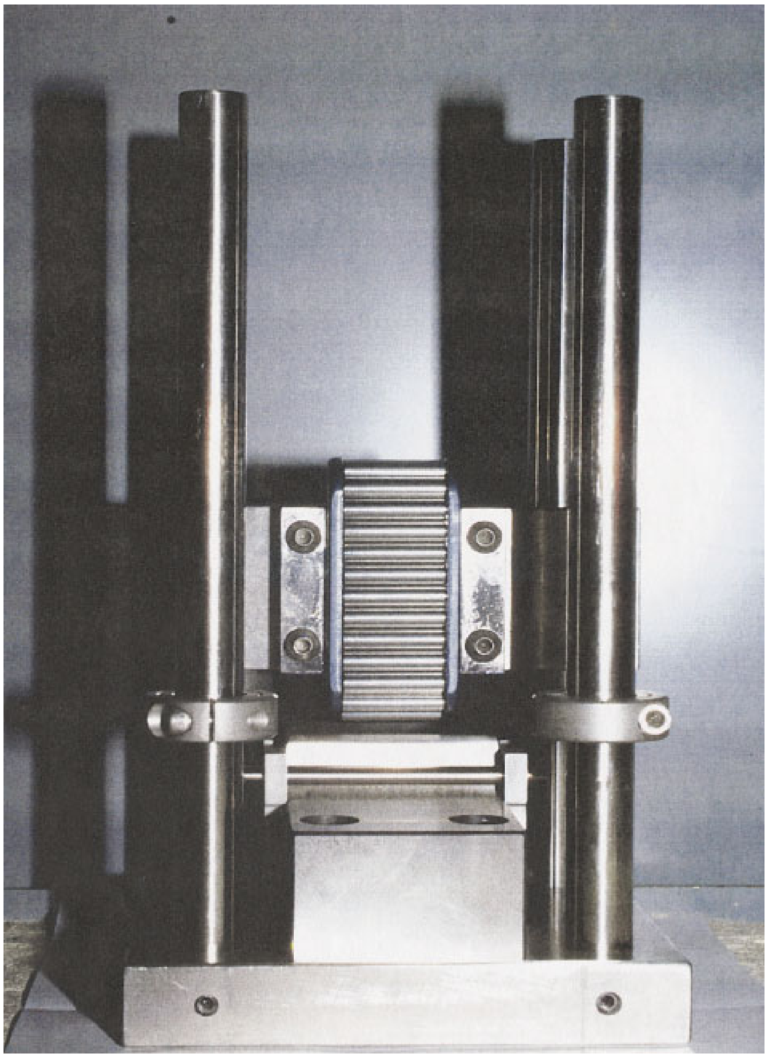

Figure 1 Roller ways and contact profile constraint (1).

kinetic energy of the car is equal to $0.5mv^2 = 0.5 \times 1000 \times (15.5)^2 = 120125$ J, where m is the mass of the car = 1000 kg (2200 lb) and v is the velocity with which it is traveling = 15.5 m/s (35 mph). In the event of an impact, the crashworthy materials would have work done on them to absorb this kinetic energy over a timeframe that ensures the deceleration of the car to be less than 20 g, above which the passengers will experience irreversible brain damage because of the relative movements of various parts of the brain within the skull cavity. Therefore, 120 kJ of work needs to be done on the crashworthy material. One can calculate the minimum safe timeframe over which this work needs to be done to ensure the safety of the passengers by using the basic equation of motion

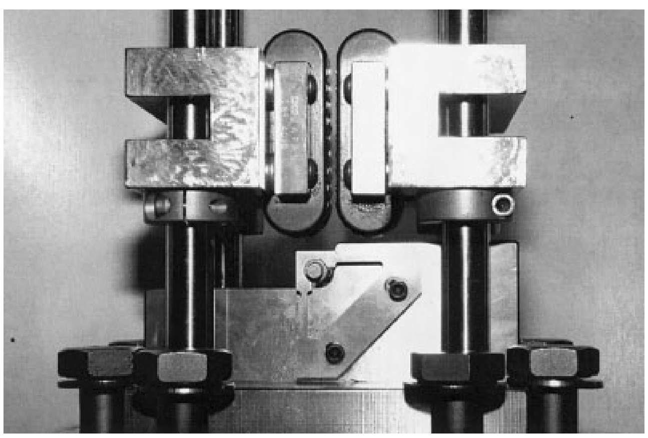

Figure 2 Roller ways and contact profile constraint (2).

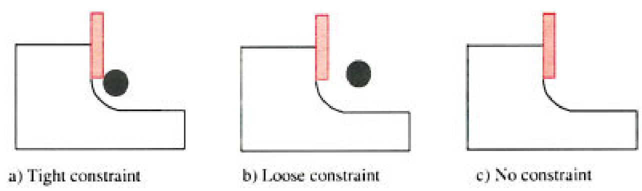

Figure 3 Constraint conditions.

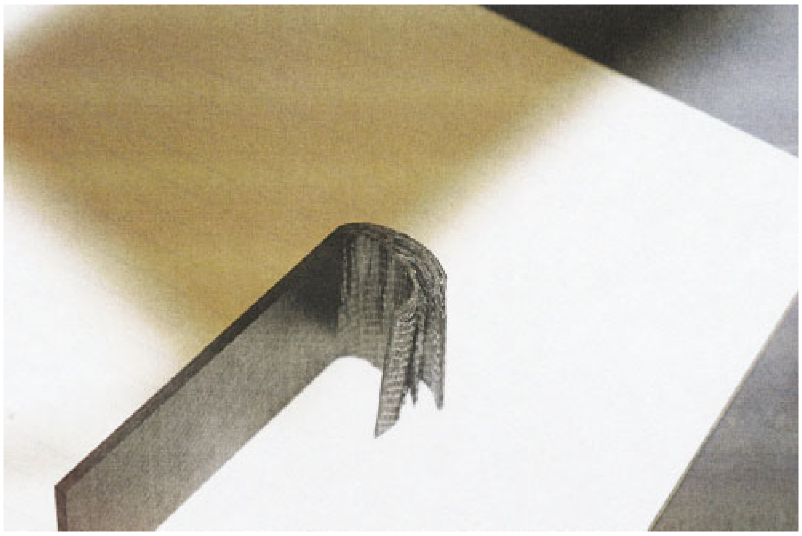

Figure 4 Crushed graphite/epoxy cross-ply laminate (CP#1) specimen plate.

$$v = u - at \quad (1)$$

where v is the final velocity of the car which is equal to 0 since the car comes to rest, u is the initial impact speed, and a is the maximum allowable deceleration, which is equal to 20 g. This minimum time was calculated to be equal to 0.079 s. Therefore, the maximum allowable rate of work decay that will ensure the safety of the passengers is equal to 120,125/0.079 = 1521 kJ/s. The SEA of the chopped carbon fiber/epoxy composite materials is recorded to be 28.11 kJ/kg. Therefore, to absorb 120 kJ of kinetic energy, one will only need 120,125/28,110 = 4.27 kg (9.39 lb) of the CCF composite material located in specific places in the car. This clearly leads to an important practical conclusion that only a reasonable amount of this composite material is required to meet the necessary impact performance standard. Figure 8 shows the amount of the different composite materials tested that will be required in the event of a crash to ensure a safe rate of work decay in a car with a mass of 1000 kg (2200 lb) traveling at a particular velocity.

WORK RATE DECAY

The maximum allowable rate of work decay that will ensure the safety of the passengers traveling in a car at 15.5 m/s (35 mph) in the event of an impact is equal to the kinetic energy with which the car is traveling divided by the minimum safe timeframe over which this work needs to be done. This was calculated in the previous section to be 1521 kJ/s. So while testing

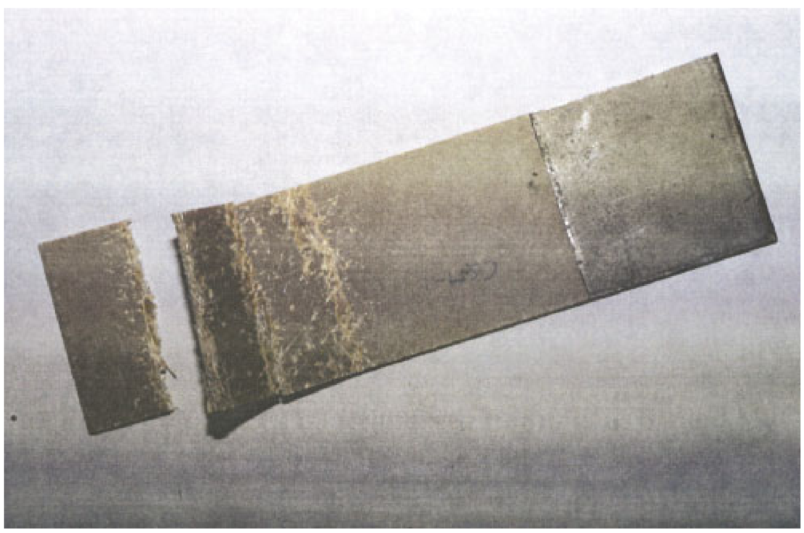

Figure 5 Crushed glass reinforced continuous strand mat (CSM) specimen plate.

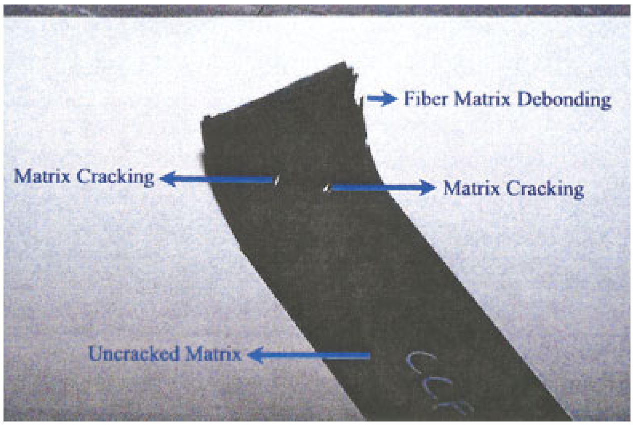

Figure 6 Crushed chopped carbon fiber (CCF) specimen plate.

materials in the lab to determine their crashworthiness, it is equally important to determine the rate of energy absorption as it is to record the magnitude of energy that is being absorbed by the specimen. No discussion of energy absorption rates can be found in literature. The load increases very rapidly in the initial stages of the load displacement curve for materials undergoing crushing to some maximum value after which stable crushing takes place. Now it is in this initial stage of the crash that the work decay rate might exceed the safe allowable limits. So although these materials may record very high energy absorption values, they will not ensure the much needed passenger safety. The best material system among all the composites investigated was identified to be the chopped carbon fiber/epoxy composite, which recorded an SEA of 28.11 J/g. One needs to further determine whether the rate of this energy absorption is within the safe allowable limits that would ensure passenger safety. The maximum allowable rate of work decay for the chopped carbon fiber composite specimens when quasi-statically crushed in a 1000-kg car traveling at 5mm/min (8.3×10^{-5} m/s) is equal to the kinetic energy possessed by it divided by the minimum safe timeframe over which this kinetic energy needs to be absorbed. The kinetic energy is equal to $0.5mv^2 = 0.5 \times 1000 \times (8.3 \times 10^{-5})^2 = 3.5 \times 10^{-6}$ J, where m is the mass = 1000 kg (2200 lb) and v is the crushing speed = (8.3×10^{-5} m/s). The minimum safe timeframe over which this work needs to be done to can be calculated using the basic equation of motion

$$v = u - at \tag{2}$$

where v is the final velocity which is equal to 0, u is the initial speed = 8.3×10^{-5} m/s, and a is the maximum allowable deceleration, which is equal to 20 g. This minimum time was calculated to be equal to 4.3 $\times 10^{-7}$ s. Therefore, the maximum allowable rate of work decay is equal to $(3.5 \times 10^{-6})/(4.3 \times 10^{-7})$ = 8.175 J/s. Similar to other composites, when the

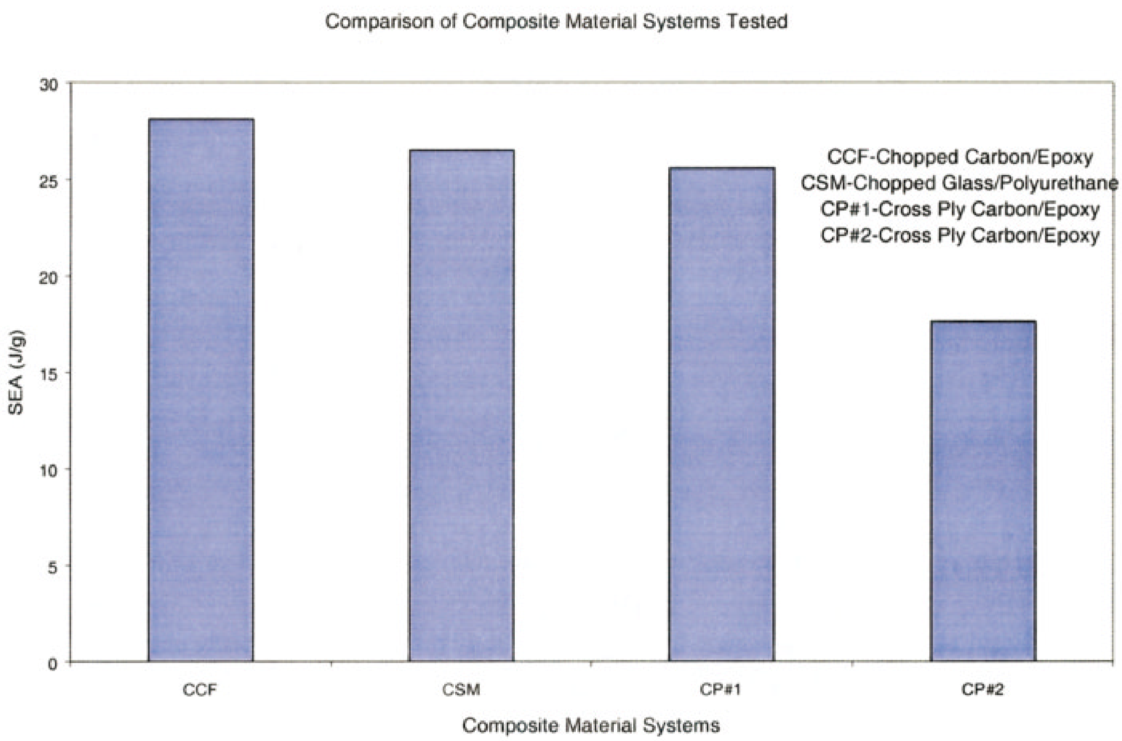

Figure 7 Comparison of composite material system tested.

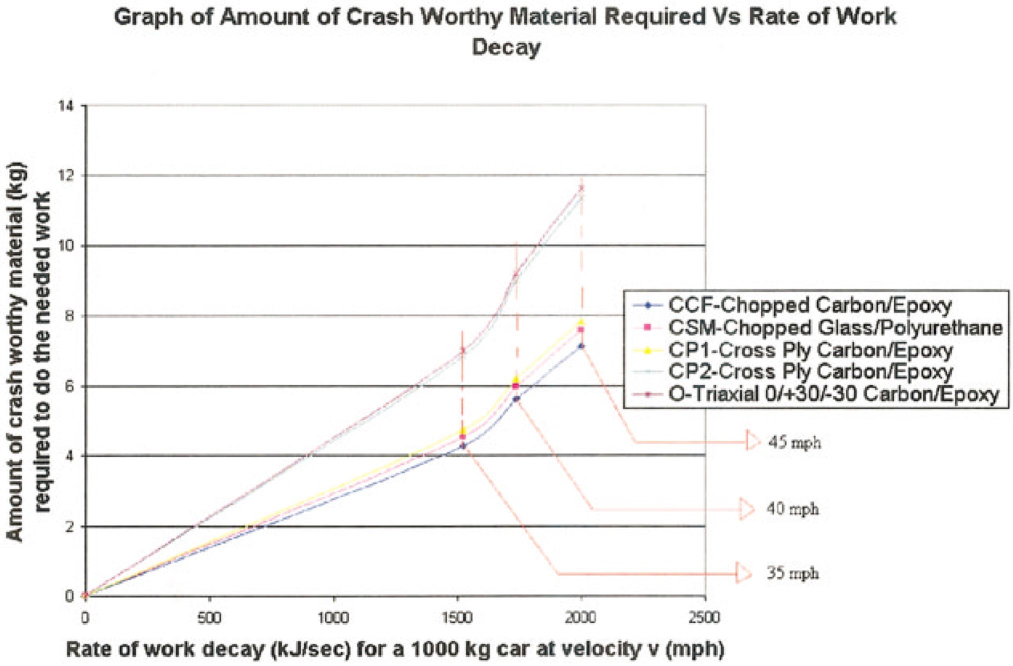

Figure 8 Graph of amount of crashworthy material required to rate of work decay.

CCF composites underwent crushing, the load increased very rapidly to some maximum value in the load displacement curve before stable crushing started taking place. It is in this initial stage of the crushing process that its work rate decay could exceed the safe allowable limits. Hence, the rate of energy absorption in this initial stage of the crush process was determined and compared with the calculated maximum allowable rate of work decay, 8.175 J/s. Calculating the area under the load displacement curve recorded during the initial stage of the crush process and dividing it by the time taken to absorb this energy accomplished this. The time quantity was determined by multiplying the x-coordinate of the initial peak in the load displacement curve by the crushing speed. The rate of energy absorption was found to be equal to 0.20 J/s, which is far less than the maximum allowable rate of work decay. Hence, it was concluded that the CCF material satisfied both criteria required for a material to be deemed highly crashworthy: a high magnitude of energy absorption and a safe allowable rate of this energy absorption.

It should be noted that the magnitude of energy absorption, the rate at which this energy is absorbed, and the maximum allowable rate of work decay are all functions of the crushing speed. At a crushing speed of 5 mm/min, the rate of energy absorption (calculated to be 0.20 J/s) is far less than the maximum allowable rate of work decay (calculated to be 8.175 J/s) and also the energy absorbed by the CCF material is high. This might not be the case at a different crushing speed, however. Cause 1: the maximum allowable rate of work decay, a ratio of the kinetic energy of the car divided by the minimum safe timeframe over which this kinetic energy can be absorbed by the CCF composite material, is a function of the crushing speed. Hence, it is this ratio that has velocity as a variable in both its numerator and its denominator that will determine the safe allowable rate of work decay. Cause 2: as reported in the literature and also in ref. 43, the SEA of a composite material is a function of crushing speed. Hence, the load displacement curve, the initial peak load, the magnitude of energy absorbed calculated as the area under the load displacement curve, and the time taken to absorb this energy are all functions of this crushing speed. Therefore, although it was concluded that at a crushing speed of 5 mm/min, the CCF material satisfied both the criteria required for it to be deemed crashworthy: a high magnitude of energy absorption and a safe allowable rate of this energy absorption, one cannot be sure about its crashworthiness at an alternate crushing speed. The above discussion further emphases the need to investigate both the magnitude and the rate of energy absorption at various testing speeds while testing materials in the lab to determine their crashworthiness.

CONCLUSION

The SEA of the chopped carbon fiber composite material was the highest compared to that of all the other composites investigated. The 50-mm (2-in.)-wide specimens belonging to a panel group having fiber tow size 150 gsm, a fiber length of 1 in., and 50% fiber volume fraction recorded the highest SEA equal to 28.11 kJ/kg when tested at 5 mm/min crushing speed under the tight constraint condition by using a profile block of radius 6.4 mm. Only a reasonable amount of it (4.27 kg) located in specific places in the car is required to meet the necessary impact performance standard. However, more work needs to be done to determine the specific places where these composite materials ought to be placed to be most useful. The CCF composite tested at 5 mm/min crushing speed met both the criteria that need to be satisfied before a material is deemed highly crashworthy: a high magnitude of energy absorption and a safe allowable rate of this energy absorption.

The high SEA recorded for the less costly CCF composite material, which by no means is an expensive aerospace grade, indicates how successful one might be in analyzing different grades and combinations of carbon fiber and resins for use in automotive applications. In design, researchers must try to better understand the design of composite parts through finite element analysis so carbon fiber composites can be concentrated in strategic locations for stiffness. The potential of using cheap glass-reinforced polymers for the basic component, then reinforcing it at critical points with the more costly carbon fiber also needs to be explored. Last, the use of carbon fiber composites for dual purposes other than just being used to improve the crashworthiness of vehicles must be explored. For example, one could use the chopped carbon fiber composite material for the reinforcements in the inside of a door in addition to its use as a crashworthy material. Its use will improve the structural integrity of the door and also the acoustics in the car. However, it must also be realized that it is going to be very difficult to replace the low-cost metals that are currently being used for parts that satisfy the functional needs in a car with a more costly carbon composite material.

FUTURE WORK

Splaying mode and frond formation is only part of the total energy absorbing process while crushing of composite plates. Alternative tests are needed to isolate and quantify the other damage mechanisms that absorb energy. An attempt will be made in the above regard to evaluate the functionality of constraint roller brackets as a load cell for measuring frictional forces.

Results from tube testing show that the dynamic SEA in tubes is less than the static SEA. The tests conducted on the CSM plates[43] also showed that the SEA in them is rate dependent. A detailed understanding of the rate dependency of damage mechanisms and SEA calls for experimental data at intermediate and high strain rates. In the above regard, modifications and/or adaptations of the existing fixture for intermediate strain rate testing will be attempted in the near future.

From the tests conducted on the chopped carbon fiber composites plates, it was concluded that fiber length appears to be the most critical material parameter controlling the SEA, with shorter fiber lengths resulting in higher specific energy absorptions.[42] Keeping that in mind, an attempt will be made to determine the effect of fiber length in tube tests.

An attempt will be made to determine the fracture toughness of the CCF material system.

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DISCLAIMER

References

1. Hull, D. Comp Sci Tech 1991, 40, 377–421.
2. Farley, G. L. Energy Absorption of Composite Material and Structures; Proceedings of the 43rd American Helicopter Society Annual Forum; St. Louis, MO, 1987; pp. 613–627.
3. Farley, G. L. J Comp Mater 1986, 20, 390–400.
4. Farley, G. L. J Comp Mater 1983, 17, 267–279.
5. Farley, G. L. J Comp Mater 1986, 20, 322–334.
6. Farley, G. L. Energy Absorption in Composite Materials for Crashworthy Structures; Proceedings of ICCM 6; Matthews, F. L.; Buskell, N. C. R.; Hodgkinson, J. M.; Mortan, J., Eds.; Elsevier Science Publishers Ltd.: London, 1987; pp. 3.57–3.66.
7. Thornton, P. H.; Edwards, P. J. J Comp Mater 1982, 16, 521–545.
8. Hull, D. in Axial Crushing of Fibre Reinforced Composite Tubes; Jones, N.; Weirzbicki, T., Eds.; Structural Crashworthiness; Butterworths: London, 1983; pp. 118–135.
9. Hamada, H.; Ramakrishna, S.; Maekawa, Z.; Nakamura, M. Energy Absorption Behavior of Hybrid Composite Tubes; Proceedings of the 10th Annual ASM/ESD Advanced Composite Conference, Dearborn, MI; 7–10 November 1994; pp. 511–522.
10. Schmuesser, D. W.; Wickliffe, L. E. J Eng Mater Technol 1987, 109, 72–77.
11. Hamada, H.; Ramakrishna, S. J Thermoplastic Compos Mater 1996, 9 (3), 259–279.
12. Farley, G. L.; Jones, R. M. J Comp Mater 1992, 26 (1), 78–89.
13. Farley, G. L. J Comp Mater 1992, 26 (3), 388–404.
14. Thornton, P. H. J Comp Mater 1979, 13, 247–262.
15. Chiu, C. H.; Lu, C. K.; Wu, C. M. J Comp Mater 1997, 31 (22), 2309–2327.
16. Chiu, C. H.; Lu, C. K.; Wu, C. M. Energy Absorption of Three-Dimensional Braided Composite Tubes; Proceedings of ICCM 10; Whistler, B. C., Eds.; Canada, August 1995; pp. 4.187–4.194.

17. Ramakrishna, S.; Hamada, H.; Maekawa, Z.; Sato, H.; J Therm Comp Mater 1995, 8, 323–344.
18. Chang, I. Y.; Lees, J. K. J Therm Comp Mater 1988, 1, 277–295.
19. Chang, I. Y. Comp Sci Technol 1985, 24, 61–79.
20. Satoh, H.; Hirakawa, H.; Maekawa, Z.; Hamada, H.; Nakamura, M.; Hull, D. Comparison of Energy Absorption Among Carbon/Thermoplastic Tubes; 38th International SAMPE Symposium, Science of Advanced Materials and Process Engineering Series, Vol. 38; 10–13 May 1993; pp. 952–966.
21. Hamada, H.; Coppola, J. C.; Hull, D.; Maekawa, Z.; Sato, H. Composites 1992, 23 (4), 245–252.
22. Farley, G. L.; Jones, R. M. Energy Absorption Capability of Composite Tubes and Beams; NASA TM-101634, AVSCOM TR-89-B-003, 1989.
23. Hull, D. Energy Absorption of Composite Materials Under Crash Conditions; Proceedings of ICCM-4; Hayashi, T.; Kawata, K.; Umekawa, S., Eds.; Tokyo, Japan, 1982; pp. 861–870.
24. Berry, J P. Energy Absorption and Failure Mechanisms of Axially Crushed GRP Tubes; Ph.D. Thesis, University of Liverpool, UK, 1984.
25. Farley, G. L. Crash Energy Absorbing Composite Sub-floor Structure; 27th SDM Conference, San Antonio, TX; AIAA: Virginia, May 1986.
26. Farley, G. L.; Jones, R. M. J Comp Mater 1992, 26 (12), 1741–1751.
27. Thornton, P. H.; Harwood, J. J.; Beardmore, P. Comp Sci Technol 1985, 24, 275–298.
28. Dubey, D. D.; Vizzini, J. A. J Comp Mater 1998, 32, 158–176.
29. Hamada, H.; Ramakrishna, S.; Maekawa, Z.; Nakamura, M.; Nishiwaki, T. Energy Absorption Characteristics of Composite Tubes with Different Cross Sectional Shapes; Proceedings of the 10th Annual ASM/ESD Advanced Composite Conference; Dearborn, MI, USA; 7–10 November 1994; pp. 523–534.
30. Mamalis, A. G.; Yuan, Y. B.; Viegelahn, G. L. Int J Vehicle Design 1992, 13 (5/6), 564–579.
31. Fairfull, A. H. Scaling Effects in the Energy Absorption of Axially Crushed Composite Tubes; Ph.D. Thesis, University of Liverpool, UK, 1986.
32. Fairfull, A. H.; Hull, D. Effects of Specimen Dimensions on the Specific Energy Absorption of Fibre Composite Tubes; Proceedings of ICCM 6; Matthews, F. L.; Buskell, N. C. R.; Hodgkinson, J. M.; Morton, J., Eds.; Elsevier Science: London, UK, 1987; pp. 3.36–3.45.
33. Farley, G. L. Energy Absorption Capability and Scalability of Square Cross Section Composite Tube Specimens; U.S. Army Research and Technology Activity–AVSCOM; pp. 1–17.
34. Ramakrishna, S.; Hamada, H. Key Eng Mater 1998, 141–143, 585–620.
35. Hanagud, S.; Craig, J. I.; Sriram, P.; Zhou, W. J Comp Mater 1989, 23, 448–459.
36. Ramakrishna, S.; Hull, D. Comp Sci Technol 1993, 49, 349–356.
37. Ramakrishna, S. J Reinforced Plast Comp 1995, 14, 1121–1141.
38. Snowdon, P.; Hull, D. Energy Absorption of SMC Under Crash Conditions; Proceedings of the Fiber Reinforced Composites Conference'84; Plastics and Rubber Institute; 3–5 April 1984; pp. 5.1–5.10.
39. Thornton, P. H.; Tao, W. H.; Robertson, R. E. Crash Energy Management: Axial Crush of Unidirectional Fiber Composite Rods; Advanced Composite Materials: New Development and Applications Conference Proceedings; Detroit, MI, USA; 30 September–3 October 1991; pp. 489–496.
40. Starbuck, J. M.; Jacob, G. C.; Simunovic, S. Test Methodologies for Determining Energy Absorbing Mechanisms of Automotive Composite Material Systems; Doc. No. 2000-01-1575; Future Car Congress, Crystal City, VA, USA, April 2000.
41. Jacob, G. C.; Starbuck, J. M.; Fellers, J. F.; Simunovic, S.; Fellers, J. F. Polymer J 2003, 35, 560.
42. Starbuck, J M.; Jacob, G. C.; Simunovic, S. Energy Absorption in Chopped Carbon Fiber Compression Molded Composites; 16th American Society of Composites (ASC) Technical Conference, Blacksburg, VA, USA; September 2001.
43. Jacob, G. C.; Starbuck, J M.; Simunovic, S.; Fellers, J F. J Appl Polym Sci 2003, 90, 3222.
44. Jacob, G. C. M.S. Thesis, Univ. of Tennessee, Knoxville, TN, 2001.