# Impact Response of Carbon-Epoxy Laminates Containing Buffer-Strip Layers

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**ABSTRACT:** This work looks at the dynamic behavior of laminated carbon-epoxy (C-E) composites with inserted interleaf polytetrafluoroethylene (PTFE)-coated material. Instrumented impact tests performed on the interleaved test samples showed significant differences in the energy absorption characteristics that could be correlated with the failure mode. It was inferred that with the introduction of small amounts of less adherent layers of material at specific locations, the load-carrying ability decreased while the energy-absorbing capability was found to improve considerably. These and other experimental observations are discussed in this article. © 2002 Wiley Periodicals, Inc. J Appl Polym Sci 85: 752–761, 2002

**Key words:** interleaved structures; impact behavior; energy absorption; damage tolerance

## INTRODUCTION

Composite materials have come to occupy a premier position among the newer materials used in aerospace and other advanced applications. However, components made from composites in such applications are prone to damage under impact. When composite structures are impacted by foreign objects, the resulting damage that occurs is governed by various energy absorption mechanisms like matrix cracking, transfiber fracture, and fiber pull-out, delamination,[1–4] and results in a change in the stiffness and strength values of the system due to the creation of delamination, etc. Many citations on the subject of impact-induced damage are available.[5,6] With a view to enhance the energy-absorbing ability of the composite system, reports on the introduction of a different material (termed buffer strips) within the fiber region of the pre-preg are available.[7]

Carbon-epoxy (C-E) composites systems are known to exhibit features corresponding to brittle failure mode. Hence, transforming such a material to absorb significant amount of energy before its failure would improve its prospects for use as an energy-absorbing material. This task could be achieved through routes ranging from careful selection of materials, design considerations, and adopting optimum processing methods. Thornton[8] indicated that structures made from polymer matrix composites with incorporation of different fibers could be designed to absorb significant energy. In the literature attempts at modification of the resin by incorporating tougheners into the matrix material can be found.[9]

Composites meant for structural crashworthy applications require that during crash-like situations the kinetic energy of the structure be dissi-

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pated in a regulated yet progressive manner. This way the dissipation could be contained within the basic structural/material element, thereby reducing the peak impact force to the subsequently posited structural elements. This containment is achievable by means of localized buckling of the section or controlled debonding and fracture process. The buckling phenomenon is assisted by suitably locating a notch of specific dimensions while the controlled debonding process can be achieved by selective incorporation of a crack arresting media in the laminate. However, all this requires a prior information on the probable path a crack might take so that the placement of the crack-arresting system in the path of the crack can effectively interrupt its growth. But in practice information of this nature is difficult to obtain or predict. Also, more than one crack may be activated during the impacting event. Hence an alternate method to deal with such a problem is called for. One such approach would be to create a preferential path for the crack to initiate and propagate and by suitably incorporating a crack-arresting media in this preferential path would then alter the energy absorption response of the system. Thus in the present work, localized regions of poor adhesion, i.e., discontinuity/defect (distributed either discretely or continuously) within the interply region of the laminates, were intentionally incorporated during the fabrication stage (refer to experimental section for details). This was done, first, with a view to create a preferential path to facilitate the damage to initiate and propagate, and second, to study the effect of distribution of such weakly adhering interply region on the impact response of the system. A point that is also included in this study is the difference in the way of crack progression occurs, following an impact event, i.e., between the laminates containing weakly adhering buffer strips (BS) and plain C-E laminates devoid of such BS layers. The work reported here also covers the influence brought out by the number of such BS layer insertions (i.e., one, two, or three) and the resulting changes in the responses to impact. Specimens were tested using an instrumented impact tester and the smoothened load/displacement data obtained were used for the analysis. The work highlights on the use of parameters evolved during the energy data analysis, and their utility in bringing out the distinction in the architecture of the samples.

## EXPERIMENTAL

Sixteen layers of carbon-epoxy pre-pregs (supplied by Ciba-Geigy) material were used to yield 5 mm thick laminates, with pieces of polytetrafluoroethylene (PTFE)-coated woven fabric (5 mm wide) inserted in between the layers. The introduction of BS layers at different positions (or layers of the lay-up) in the form of either continuous or discontinuous lengths was accomplished during the lay-up stage. The woven PTFE-coated fabric (due to its mesh-like openings) allowed for the resins to establish contact. The region constituted by the immediate environs of this PTFE-coated material corresponds to areas of less-adhesion owing to the poor bonding nature. These, being prone to a debonding process, were abbreviated BS, connoting buffer/delaminating strips, in this work. How this localized change in structural detail affects firstly the energy absorption levels and then the way the crack propagates in the sample in both plain and strip bearing C-E systems in both continuous and discontinuous strip bearing laminates as well as paying attention to the place of impact vis-à-vis the positing of the discontinuous strip form the principal aims of this investigation. To achieve these goals initially only C-E samples were made. These were termed "plain" and given a code "0" as it had no PTFE, i.e., buffer strips (BS) inserted within them. In making the next category, the BS was introduced in the midplane, and given a code starting with the number "1" as only one layer region containing the BS was inserted at midthickness. For the third variety, BS was introduced at two planes—namely, one third and two third (i.e., along thickness) layers—and these were coded with a starting number "2". In the case of the fourth and last category, the BS was introduced at three places namely one fourth, one half and three fourth layer positions (again along thickness). These samples were designated with a starting numeral "3."

The above three categories of BS′-bearing specimens (i.e., series starting with 1, 2, and 3) were further subclassified depending on whether the BS′ introduced in the laminate were in the form of continuous lengths or discontinuous strips as mentioned earlier: (i) The laminates containing continuous PTFE lengths were abbreviated "CT" in this work and depicted in Figure 1(a). (ii) The laminates containing discontinuous delaminating strips (symbolised by the letter "D") were made with the PTFE lengths being discretely distributed along the length with interspersing spaces of

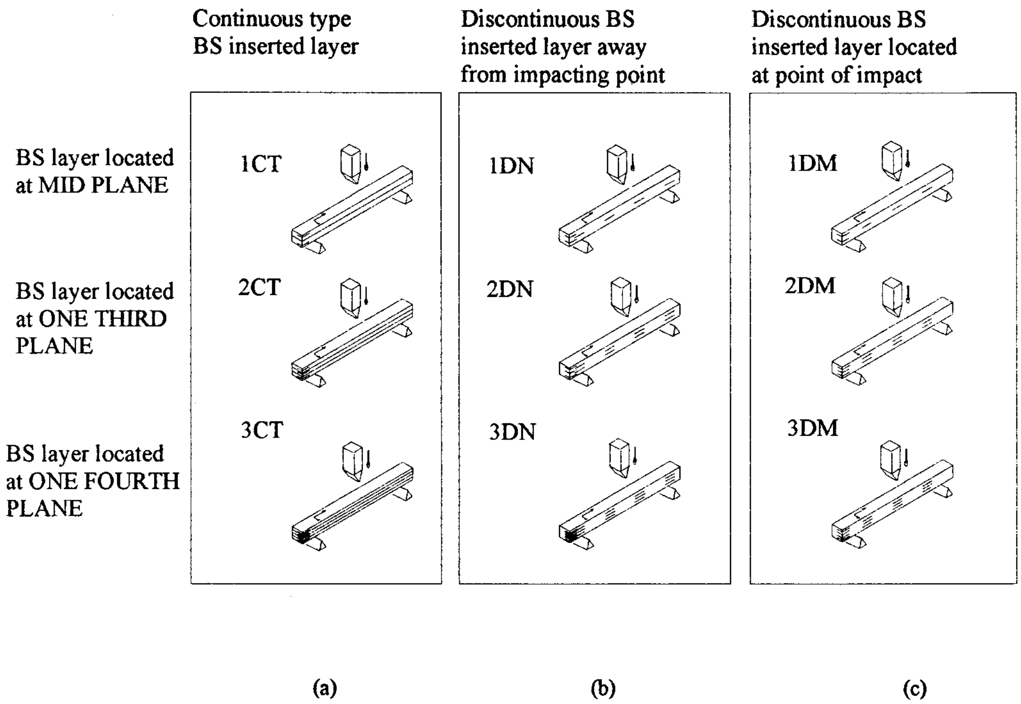



**Figure 1** The different arrangements of BS-inserted layers within the specimen and their codification.

12 mm between adjacent strips in the latter category. These discontinuous varieties, due to the basic nature of discontinuity, offers two lay-up arrangements: (a) In one case, the point of loading was positioned such that it is away from the location of strips and termed nonmiddiscontinuous [i.e., "DN" to make it short in this work, Fig. 1(b)]. (b) In the second case of the same subclass of the discontinuous delaminating strips, the BS materials were so located that they lay exactly below the point of loading. This arrangement was made possible by planning the sectioning of the test coupons from the fabricated laminates and these were called discontinuous delamination strips at mid [or "DM" to be brief, Fig. 1(c)]. Thus from a processing schedule involving both type of PTFE strips (i.e., continuous and discontinuous) and their location(s) across as well as along the thickness directions it was possible to get a combination of nine types of specimens with the following codes: 1CT, 1DN, 1DM; 2CT, 2DN, 2DM; 3CT, 3DN, and 3DM, respectively, allotted (see Fig. 1). These nine strip-bearing test specimens were tested in impact mode using an instrumented impact testing (DYNATUP 830; courtesy Central Power Research Institute, Bangalore) machine under ambient conditions. The test was carried out using the falling weight method in the flat mode of positioning, i.e. the stack layers for this mounting were perpendicular to the impacting direction [Fig. 1(a,b,c)]. Specimens were cut to a size of 5 × 5 × 55 mm using a diamond cutter. This geometry of specimen with no notches falls in the domain of a nonstandard specification. However, as the primary purpose was to evaluate and relatively grade the response to impact, the above geometry was considered acceptable. Further, for a relative type of grading, envisaged in this work, it was considered useful to have values of the plain C-E as a reference one and normalize the data derived for the other cases. The effects of inserted BS′ and their influence on the trends in energy–time plots as well as the fracture mode/features were looked into in this work. A 3.2 kg hammer mass, with an impact velocity of 2.97 m/s, was used during the experiments to yield an impact energy of about 13.5 J.

## RESULTS AND DISCUSSION

### Energy Data Curves

Figure 2(a) records the relative changes in energy absorption values that occurs when increasing numbers of strip layers are inserted either as a

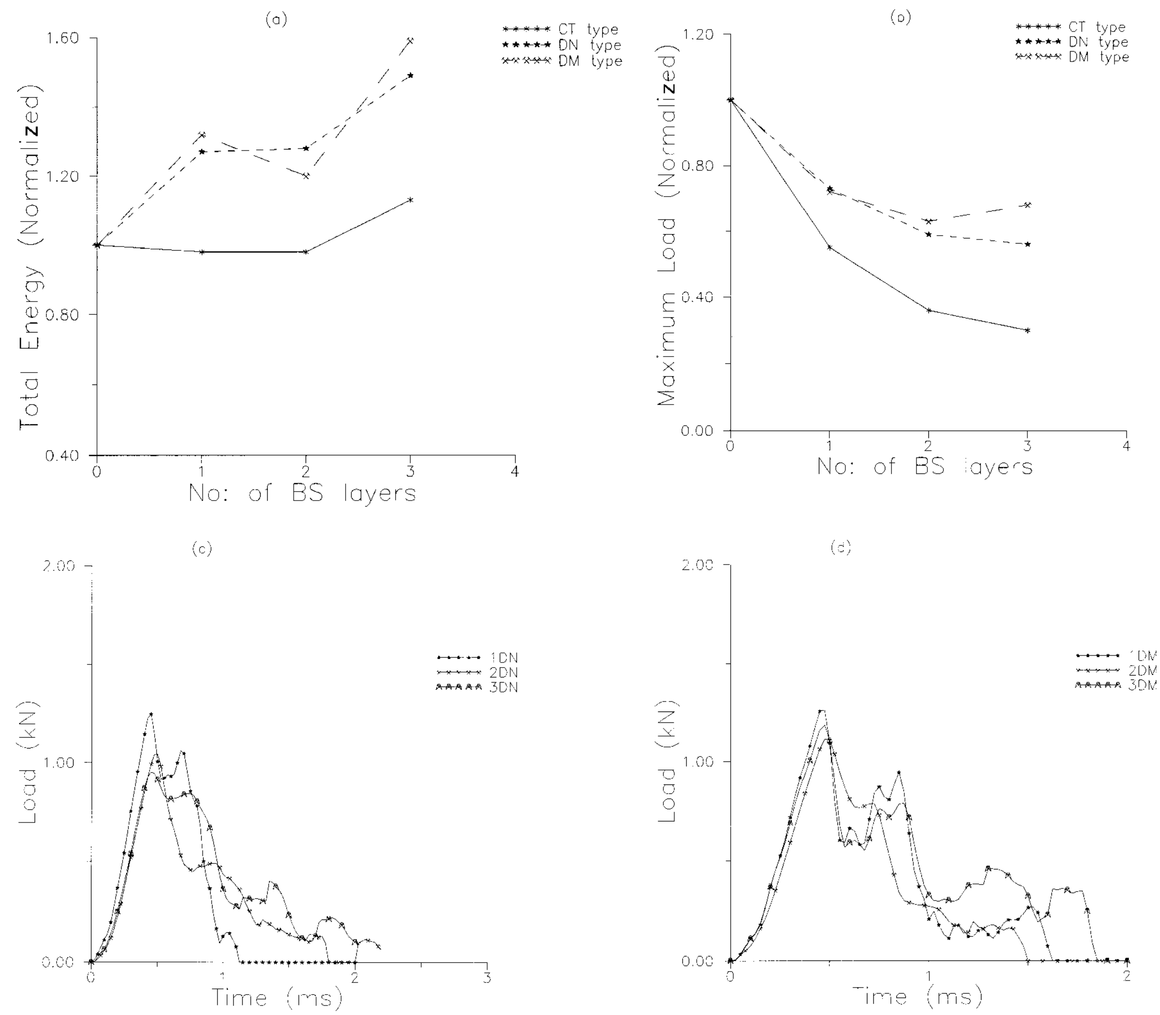



**Figure 2** A plot showing the variation of (a) normalized energy; (b) normalized load with respect to the number of BS insertion for various types of specimens; (c) and (d) load-time trace displaying multiple peaks for DN- and DM-type specimens after the maximum load event for all cases of BS insertions, respectively.

continuous or discontinuous medium in the C-E system. It may be seen that by and large an upward value change occurs due to the insertion of an interleaf material either singly in one layer or as numbers of such single layer at different lay-up positions. From the data for continuous BS-bearing medium [Fig. 2(a), bottom curve], it is seen that with the insertion of first BS layer (i.e., in 1CT sample) there is an insignificant reduction in the energy absorption. The same small level change in the energy value (but this time an upward one) occurs with the second layer insertion also (i.e., 2CT). However, for the case of a three-layer insertion, there is a noticeable upward change indicating the utility of inclusion of more number of continuous BS layers in the material [Fig. 2(a)].

When the data for discontinuous BS-bearing system is considered, it is noticed that while the DN variety maintains a positive upward gradient (like in CT case discussed above) for all (i.e. 1-, 2-, and 3-layer) cases of BS insertions, that for the DM variety, the continuous positive gradient, is absent [Fig. 2(a)]. This behavior with 2DM is unusual when compared to equivalent systems like 2CT and 2DN samples. It is of relevance to note at this juncture that only for this two-layer arrangement (i.e., 2CT, 2DN, and 2DM), there is no BS layer corresponding to the neutral axis (NA) associated with bending of beams. But to explain the different behavior of 2DM recourse to macroscopy is taken in a section to follow.

When the total energy absorbed by the test sample is considered (Table I), specimen with con-

**Table I A Tabulation Listing the Average Values of Maximum Load, Total Energy + Time for Different Set of Samples**

| Type of Specimen | Maximum Load (kN) | Total Energy (J) | Total Time (ms) |
|---|---|---|---|
| Plain | 1.78 | 1.45 | 0.58 |
| 1CT | 0.99 | 1.43 | 1.10 |
| 2CT | 0.65 | 1.47 | 1.47 |
| 3CT | 0.57 | 1.65 | 1.8 |
| 1DN | 1.31 | 1.75 | 1.00 |
| 2DN | 1.06 | 1.89 | 1.77 |
| 3DN | 1.00 | 2.17 | 1.88 |
| 1DM | 1.27 | 1.91 | 1.21 |
| 2DM | 1.12 | 1.75 | 1.34 |
| 3DM | 1.17 | 2.35 | 1.77 |

tinuous BS bearing (CT type) showed a value nearly 98% to that of the plain C-E specimen (i.e., devoid of strips). Samples with discontinuous BS′ insertions (DN and DM), on the other hand, yielded absorbed energy values which were about 30–60% higher than that recorded with the plain C-E sample (Table I).

With regard to load values listed in Table I, it can be seen that the values generally record a decrease with an increase in number of BS′ insertions in the samples irrespective of whether the strips are continuous or discontinuous type. A discussion of the load aspect forms the subject of an earlier report.[10] Like in the energy data [Fig. 2(a)], discussed earlier, here too [Fig. 2(b)] the CT and DN varieties show a commonality in the trend in that both record the same pattern. The load data for DM samples, like the energy data presented before, continue to show a different trend especially involving the 2-BS layer insertion case.

From the load-time curves (obtained on the recorder of instrumented impact test setup), an observation noticed for the discretely distributed BS′-bearing samples (DN and DM) with considerable regularity in occurrence was the existence of a few more peaks following the maximum peak [Fig. 2(c) and (d)]. In this analysis, it was hence decided to look into such occurrences and examine their possible role in changing the energy absorption characteristics of the specimen. For this purpose a novel approach of associating each peak representing a fracture event, with an initiating stage symbolised by $E_i$'s and a propagation stage designated $E_p$'s, was adopted. Further, as influence of BS inserted layer gets best reflected in the response of the system to instrumented impacts, the $E_i$'s and $E_p$'s corresponding to first peak, $E_{i1}$ and $E_{p1}$, are included in this analysis at this stage. The schematic representation of the peaks and the corresponding zones are depicted in Figure 3.

This first peak data will now be used to analyze for the characteristics of CT- and DN-type specimens, which showed commonality of features for both the energy and load data trends discussed earlier, while DM samples showed a different pattern compared to CT. For doing this kind of study, a new energy parameter $E_A$, given by the expression:

$$E_A = (E_{i1} - E_{p1})/(E_{p1}/E_{i1}) \quad (1)$$

is introduced in this work. The exhibition of either a commonality or a difference in response to impacts in discontinuous strip bearing samples (i.e., DN or DM), with respect to continuous (CT) ones, appears to be exclusively dependent on where the strip is located, vis-à-vis the loading point. When the loading is chosen so as to coincide with the zone containing no inserted strips (i.e., the nonmidzone as in DN sample), one type of trend leading to continuous decrease in $E_A$ results. The plots comparing the plain samples are shown in Figure 4(a).

On the other hand, when the samples containing buffer strips in the loading zone, as in DM samples, are subjected to impact, a different sit-

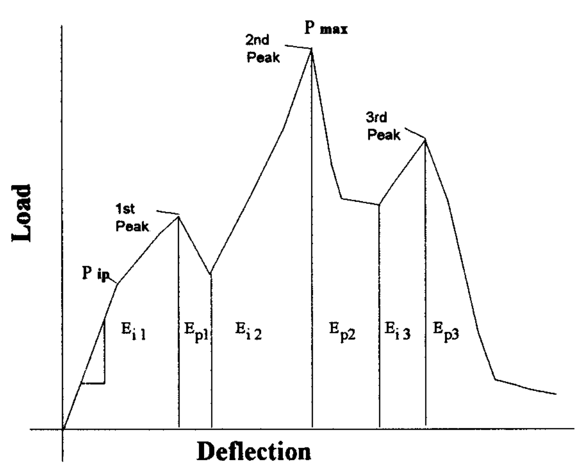



**Figure 3** Schematic load-deflection plot showing sequential regions of initiation and propagation marked $E_i$'s and $E_p$'s for pre- and postmaximum load events, respectively.

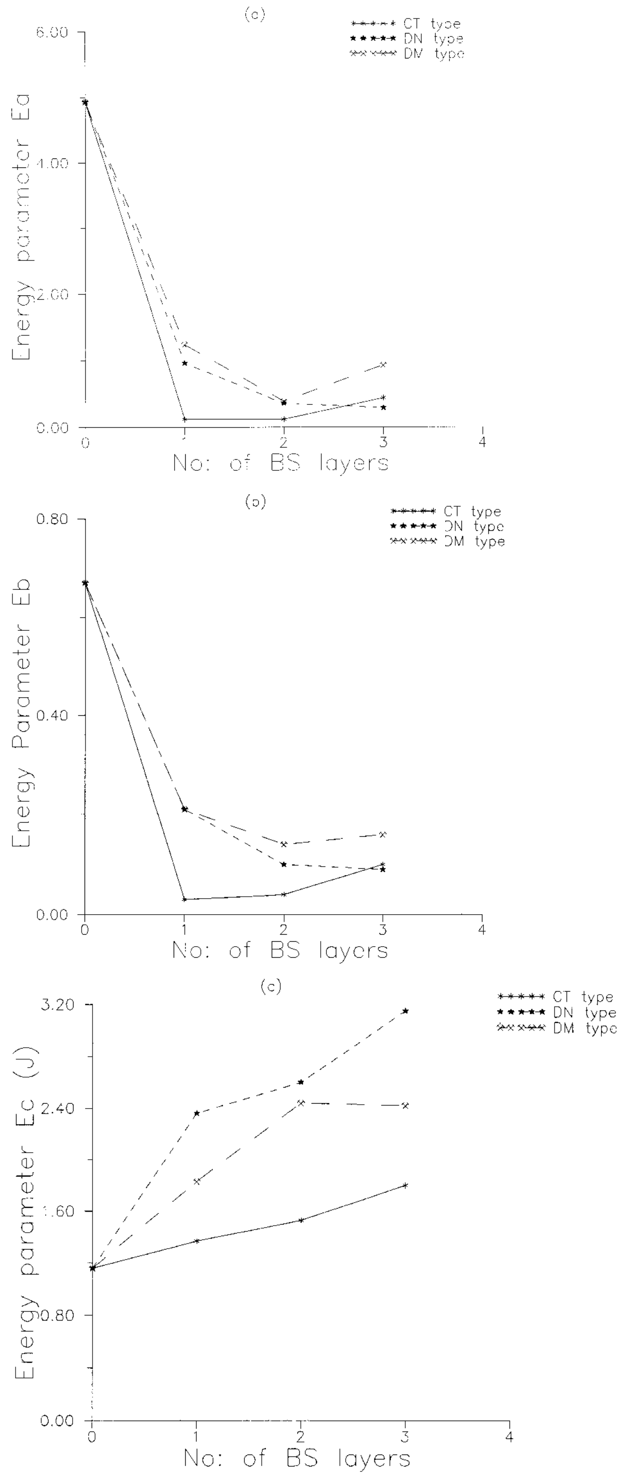



**Figure 4** A plot showing the different parameters (a) $E_A$, (b) $E_B$, and (c) $E_C$ with varying BS insertions for all varieties of specimen.

uation is noticed. There is a drop in the $E_A$ value for the 1- and the 2-layer insertion while the 3-layer insertion case shows a small rise. This way the discontinuous strip bearing DM samples behaves like the continuous CT samples for this $E_A$ parameter [Fig. 4(a)]. In other words, the data curves for these two sets of samples run near parallel for the different number of BS′ insertions. This trend is on expected lines, because the difference between DM and CT is that the strip is continuous in the latter, while it is discontinuous in the former, and in both cases the BS strip is positioned under the loading point.

Between DN and DM sets they again display a difference in the response to impact. This is attributed to the positioning of the BS layer vis-à-vis impact loading point. Hence from this kind of approach the viability of this parameter as a tool to distinguish the sample with different BS layer locations and also the type of the BS strip was explored.

Continuing along these efforts further, it was decided to look into the existence of a parameter that can uniformly bring about the change in value for 1-, 2-, 3-layer BS′ insertions. The ratio selected this time has in the denominator the $E_{\text{Total}}$ given by sum of $E_p$ and $E_i$[11] terms [unlike $E_A$ of eq. (1), having the ratio of $E_p/E_i$] associated. The new parameter is designated $E_B$ in this work and is mathematically expressed as

$$E_B = (E_{i1} - E_{p1})/E_{\text{Total}} \tag{2}$$

It may be seen that the numerator term used in the earlier parameter $E_A$ [eq. (1)] is retained in this newer $E_B$ parameter [eq. (2)]. The data for this parameter shows a gradation in which CT exists as the lowest curve, while DN and DM come above this [Fig. 4(b)]. Here, unlike in Figure 4(a) for $E_A$ discussed earlier, there is no crossover point at any stage. However, despite a better graphical representation, still some commonality of the paths can be found. Hence, to make the investigation more comprehensive, it was decided to look for a different parameter that can distinguish each of the BS′-bearing (i.e. CT, DN, and DM) samples employed in this work uniquely. The parametric term tried for this is designated $E_C$, which is expressed as

$$E_C = [1 - (E_{i1}/T_{i1} - E_{p1}/T_{p1})] \times T_{\text{Tot}} \tag{3}$$

where $T$'s stand for time duration for initiation ($T_{i1}$) and propagation ($T_{p1}$) stages corresponding to the first peak in the load-time plots recorded by the instrumented setup. In this approach the

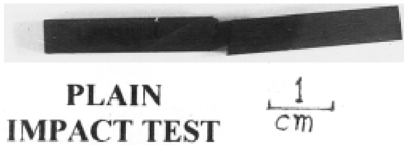



**Figure 5** Photograph showing the transverse failure mode of the plain sample.

power for initiation is subtracted from the power for propagation and the resulting difference in power is multiplied with the total time taken by the experiment to give an energy dimension.

The plot for $E_c$ is shown in Figure 4(c). In this case the impact energy responses for all the three cases are distinctly brought out. The CT sample is positioned at the bottom-most, and following this and on expected lines the curve for the DM samples (both having BS strip layer inserted at and including the neutral axis as mentioned before) lie. Above these two is positioned the data curves pertaining to the DN sample. Hence this parameter can be utilized to best distinguish the C-E system without and with three differently posited interleaved layer materials.

## Macroscopy

Considering the plain variety first, i.e., without any BS layers insertion, a better bonding between the reinforcement and matrix regions was expected. Consequently, it displays much less delamination along the specimen length (Fig. 5). However, it shows proneness to go through the thickness (i.e., along the direction of impact) crack propagation, which is a least traversing path as far as the total distance traversed by the crack is concerned. Consequently, the energy absorbed is low. On the contrary, should the crack get initiated along the thickness but later on grow in perpendicular direction involving the interface between the inserted BS layer and C-E system, the crack path experiences a detour. This detour of the crack path under normal circumstances should lead to higher energy absorption levels. However, owing to the weaker interface, involving the PTFE and C-E system, which is prone to debonding, there could be a lowering of absorbed energy values. Hence, depending on the scale of the two competitive (opposing) processes, the energy absorption can be marginally low (as in 1CT vis-à-vis plain sample) or somewhat higher as in 2- and 3CT samples (Table I). Considering the postimpact macroscopy features, 1CT-bearing samples show a feature involving not only splitting along the horizontal section but further sectioning into two parts along the thickness, resulting in four segmental parts in all [Fig. 6(a)]. Incidentally, the longitudinal separation that is favored in the inserted BS layer in 1CT sample is evident in this figure. This observation (longitudinal splitting tendency) is also replicated in both 2CT and 3CT samples shown in Figure 6(b) and Fig 6(c), respectively, except for the difference in the number of such splitting that correlates well with the number of BS insertion layers.

Thus the 1CT sample with one BS insertion shows one longitudinal splitting when viewed lon-

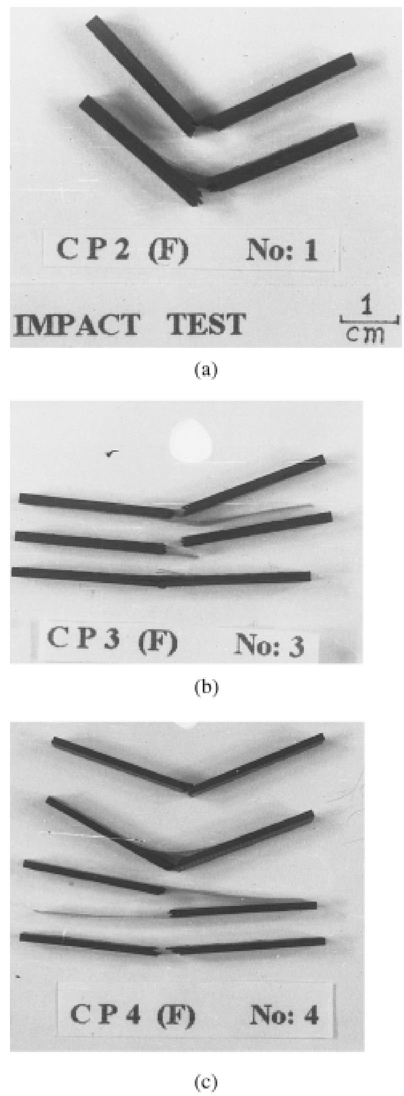
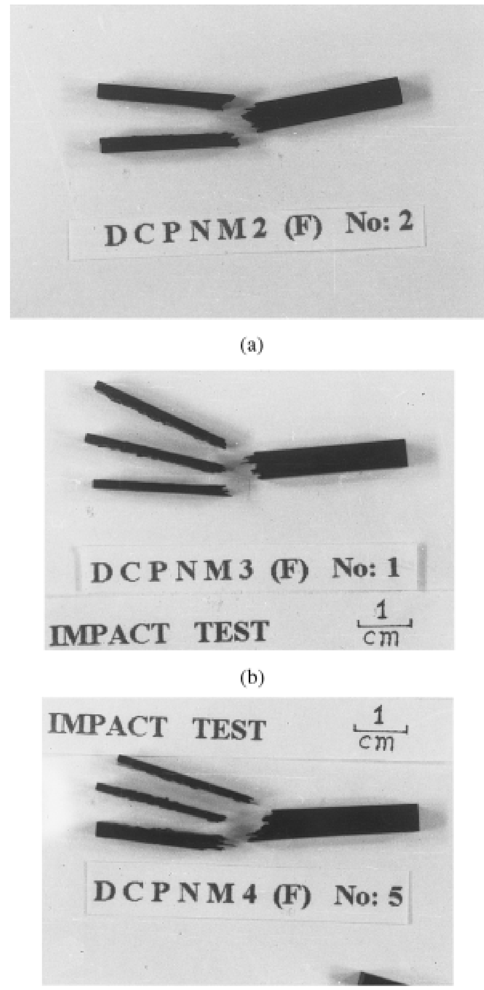



**Figure 6** Picture showing the longitudinal splitting up of the CT-type specimen with (a) one (b) two, and (c) three BS insertions.




(c)

**Figure 7** Picture showing the splitting pattern of the DN-type specimen with (a) one, (b) two, and (c) three BS insertions. (Note the one-sided splitting pattern.)

gitudinally [Fig. 6(a)]; the 2CT sample with two insertions displays two longitudinal splits [Fig. 6(b)]; and lastly, the 3CT sample exhibits three such splits corresponding to the three insertions [Fig. 6(c)]. Thus with increasing number of BS insertions for CT type, they show consistency in the correlation of the data with that of the macroscopic observations. Further, when the macrograph of these different CT samples are examined carefully, it is noticed for instance that the compression side of 2- or 3BS layers bearing test samples, generally stating, show proneness to being somewhat attached, while the tension side displays a transverse fracture feature.

With regard to the discontinuous variety it is observed that invariably in all the specimens, whether belonging to DN or DM type, the failure is a combination of features involving both through the thickness as well as longitudinal splitting-up [Fig. 7(a) to 8(c)]. However, unlike the previous case where the CT-type specimen showed a complete longitudinal splitting-up on both sides of the load application point [seen in Figs. 6(a), 6(b), and 6(c), depicted earlier], here in this case only one half of the test sample has responded to impact involving split and/or delamination. In other words, the longitudinal splitting-up is restricted to any one side of the load application point. This alteration in the traversing length of the delamination accounts for the change in the load-bearing capability and the energy absorption characteristics of both these, i.e., the DN and DM discontinuous BS-bearing sample vis-à-vis either the continuous BS′-bearing CT or the plain (C-E) varieties. Also, longitudinal splitting for the case of DN and DM samples, generally stating, is observed to be restricted to the tension-dominated side of the neutral axis for instance [Fig. 8(b)].

Summing up the macroscopic observation, the plain variety samples devoid of any BS insertion display effective adhesion and therefore show very less delamination. On the other hand, they display proneness to transverse, through the thickness-cracking phenomenon requiring minimum traversing path, as stated earlier and hence correspondingly registers a lower energy value for crack propagation. 1CT samples show a through-thickness crack up to the inserted layers and thereafter the crack follows an alternative path in the form of diversion to the plane containing the BS layers that is perpendicular to the initially grown direction. Similar is the case with 2CT and 3CT varieties, which show that as more and more of BS layers are introduced, the failure pattern changes from an entirely transverse through thickness crack (for the plain sample) to predominantly delamination-governed failure for continuous BS-bearing C-E test coupons. This observation is on expected lines as the introduction of BS layers was made to achieve the tasks of carefully tailored crack initiation, propagation, and detours.

As regards the higher level of energy absorption in discontinuous (DN and DM varieties) compared to continuous (CT) varieties [Fig. 2(a)], it is evident that where BS′ are located the debonding occurs readily, while it experiences a resistance in its growth in the region where the BS layers are absent. From the macrography of discontinuous BS layer bearing samples, generally stated it is

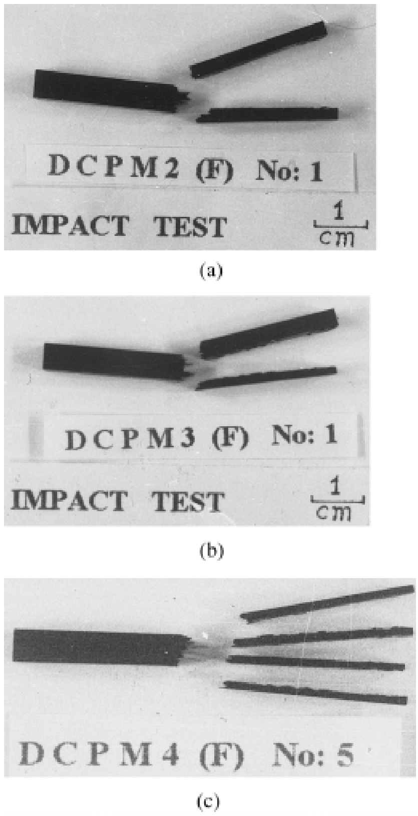



**Figure 8** Picture showing the splitting pattern of the DM-type specimen with (a) one, (b) two, and (c) three BS insertions.

observed that the delamination initiation and spread is confined primarily to the layers where BS′ layers are inserted [Fig. 7(a) to 8(c)], which goes to prove the effectiveness of such layer insertion. Thus once a delamination is initiated in the plane containing the BS, it propagates at a particular rate depending on factors like adhesion and local stiffness mismatch between the stacked laminae. When the propagating crack front encounters the BS region, the rate of crack propagation increases owing to the poor adhesion property associated with the PTFE-coated buffer strip. In either case, at the point where the BS-containing region ceases to exist, the crack path experiences a temporary arrest in its progression. This condition remains till such time when the stress builds up to the threshold level for the crack initiation and propagation to resume in the region outside the BS zone, so no instantaneous growth of cracks, which have reached the end of the strip, can occur. This is the phase where a change in the crack propagation rate is effected. This alteration of the crack propagation rate due to the discontinuity that is deliberately introduced into the lay-up sequence is effectively made use of in the enhancement of the energy absorption levels involved in the process. Consequently, the energy absorption in the discontinuous variety changes significantly when compared to both plain and continuous BS-bearing material.

Also, this cycle of alteration that a crack experiences in its propagation can be invoked to account for recording of both multiple raising trends for the load part of the curve [Fig. 2(c) and (d)]. This argument gets support when the work of Dharani and James[12] is considered, where it has been shown, based on shear lag theory, that the force for crack propagation increases at the interface. One immediate offshoot of this delayed response is an increase in the energy absorption in the samples possessing the deliberately inserted PTFE strips. Thus the insertion of BS at certain locations and specified numbers, during the lay-up, can add to the energy absorption capacity.

As regard the issue highlighted earlier—namely, between 2DN and 2DM where the energy absorption in the former case was slightly higher than that seen in the latter (Table I),—a resort to macrography obtained on the two samples is made in this work. Thus, on comparing the failure patterns of these varieties [Fig. 7(b) and Fig. 8(b)], corresponding to 2DN and 2DM, respectively, it is very evident that with the absence of a BS strip at the point of loading (in DN variety), the transverse crack, initiated along the thickness, persists as a delamination in both the interface regions containing the two inserted layers [Fig. 7(b)]. Consequently, the number of separated layers following impact is more in the non-mid-DN variety, thus requiring higher energies. In DM, on the other hand, the ready availability of the PTFE layer at the point of impact gives a preferential path diversion by 90° for the propagation of delamination along one of the two inserted PTFE/C-E regions, and hence the number of separated layers as well as the length of the detour path is accordingly lower. Thus the higher energy recorded by the 2DN samples when compared to the 2DM varieties can be traced also to the alteration of the fracture path brought about by the basic architectural differences existing between DN- and DM-type specimens.

## CONCLUSIONS

- The size of the buffer strip has a direct influence on the energy absorption characteristics of the samples. While the BS′ variety, which is of continuous form like in the CT type tend to reduce the energy absorption values, those that are a discretely distributed BS type (i.e., DN or DM type) increase the same.

- The number of the BS layer insertion has a direct bearing on the impact response in that the absorbed energy values increases with an increase in the number of BS′ insertions.
- The fracture path of the BS-bearing sample is preferred along the layers containing BS insertions.
- By introducing BS (PTFE) strips within the preferential fracture path, the crack propagation was made to undergo a cyclic alteration in its propagation rates. Such alterations coupled with the multiple initiation of the crack in the same plane enhanced the energy absorption capability of the discontinuous system considerably.
- Finally, a parameter $E_c$ could be evolved that could effectively be used as a tool to unambiguously differentiate the architectural differences that exists in the various types of specimens studied in this work.

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