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Low-energy repetitive impact in carbon–epoxy composite

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The reduction of the strength of a carbon fibre composite after impact is an important consideration in design. During routine maintenance activities and during operation, composite components may be subjected to repeated impact at localized sites. The resultant damage may seriously impair the subsequent mechanical performance of the composite. Thus, it is appropriate to investigate the effects of repeated impact on the residual strength of structural composite materials. The paper reports and discusses investigations made to identify and characterize the response of laminated carbon–epoxy composites to low-energy repetitive impact. The residual strength after impact at various absorbed energy levels and different numbers of impacts has been studied for this material system by three-point bending. The investigated energies are in the range of 2–5 J and the maximum number of impacts is 405. Correlation has been found between a new variable comprising the logarithm of the product of number of impacts with the impact energy and the residual strength of this composite material system.

1. Introduction

Composite materials are very sensitive to impact, especially carbon fibre reinforced polymers (CFRP). The strength reduction or the residual strength (RS) of CFRP as a result of impact is thus an important consideration in design. The resistance of a CFRP structure to impact is particularly important when considering the use of these materials in critical structures such as aircraft. Frequent impacts in aircraft are likely from hail, bird strikes, runway debris and from ground service equipment. The ground service equipment impact energy is in the range of less than 10 J. It has been reported [1] that tool drop is the most common type of impact experienced by naval aircraft during service. Thus, during routine maintenance activities and operations, composite components may be subjected to repeated low-energy impact, at localized sites. In the specific area of low-energy repetitive impact (LERI) little has been published.

In low-energy impact the damage is confined to the matrix and little fibre damage occurs. Therefore the in-plane tensile strength of the laminate may not be seriously degraded, but the damage in the matrix and interface is significant. The fracture path due to impact coincides with low-strength matrix dominated planes. This includes delamination in the interface between plies and diagonal shear cracks in the matrix between transverse oriented fibres [2].

Two techniques for simulating LERI are reported in the literature: drop-weight impact (e.g. [3]) and cantilever-type steel ball (e.g. [4]). In the following research a different LERI system is employed. The system is based on utilizing the energy-storing property of a spring. This is done when a spring is put into tension by mechanical means, e.g. a cam. A schematic illustration of the current LERI system is shown in Fig. 1 and described below. If a helical spring is extended or compressed, potential energy is stored in the form of strain energy. The amount of stored energy is a function of the displacement of the spring according to $U = \frac{1}{2} kx^2$. This is an easy quantity to determine. The essentials of the apparatus are a rocker arm, a cam and a helical tension spring as illustrated in Fig. 1. The cam rotates on a shaft where the speed of rotation can be varied. As it rotates it causes the rocker arm to pivot. The spring is extended until the follower surface on the rocker arm in contact with the cam moves over a step on the cam. The follower effectively "ramps"

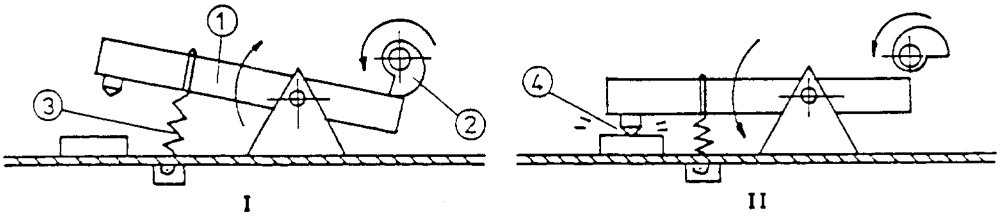

Figure 1 Schematic presentation of the impact system: (1) rocker arm, (2) cam, (3) tension spring, (4) impact point.

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over the step so that the tension in the spring can be released. The rocker arm is then pulled rapidly back to its rest position, thereby producing an impact at 4 in Fig. 1. Additional details of the impact system can be found in Fricke [5].

In the literature a wide range of specimen dimensions and supports are studied for impact research of composites. Cantwell *et al.* [3] used 300 mm × 1000 mm plates with a 100 mm diameter ring clamped support. Lal [4] used circular plates 100 mm in diameter and a 100 mm diameter ring clamped support. Boll *et al.* [6] used 100 mm × 150 mm plates centred on a 76 mm × 127 mm edge support. The variety of specimens and supports indicates that a single standard specimen size for impact testing is unlikely.

In this research, rectangular specimens which are supported through their entire area by an anvil are investigated. The reason for this supporting mode is motivated by a new utilization of composite materials. In this application the composite is used as fire-retarding cover for an aluminium fuel drop-tank on fighters. During service this composite cover suffers from LERI when it is supported over its entire area by the tank. Thus, the current type of support for the LERI specimens is a practical simulation of the in-service life of this composite material system.

Various researchers have investigated the impact effect on the RS of loading the composite in tension or compression (e.g. [3, 4, 7, 8]). In the present research the post-impact RS is investigated when the specimens are subjected to three-point bending in a span-to-depth ratio (SDR) which induces delamination. The motivation for this loading mode is that it provides a common and simple measurement for characterizing the composite shear strength. This property is matrix and/or interface-dominated, a material component which is affected by the impact.

The objective of this research is to investigate the effect of LERI on the RS of angle-ply CFRP. The study is based on a comparative examination. The effect of various number of impacts, NOI, and energies on the RS is compared with the strength of reference samples. The following topics are investigated.

1. Reference specimens; characterizing their failure mode and ultimate strength.
2. Characterization of external and internal damage in specimens which have been subjected to various impact conditions.
3. Characterizing the RS of the impacted specimens and comparing it with the reference sample strength.
4. Characterizing the impact effect on the failure mode.

2. Experimental procedure

The LERI system employed is illustrated schematically in Fig. 1. The impactor (numbered 4 in Fig. 1) is a 12.7 mm diameter hemisphere. The applied energies are 2, 3, 4, and 5 J (the LERI system is designed for maximum of 6 J). The investigated NOI are 5, 15, 45, 135 and 405, arbitrarily chosen.

The specimens were cut from a 2.2 mm thick laminated plate with 60 vol % fibres, 16-ply $[0/\pm 45/0]_{2S}$ IM6 Hercules carbon fibre with DER 3130 DEGBA epoxy. In Fig. 2 the specimen dimensions and the impact site (designated by a star) are illustrated. From this asymmetric impact location an approximation of the internal impact damage area can be provided. This is implemented by polishing the specimen's through-thickness surfaces for light optical microscope inspection. The examination is conducted after the impact, before loading. Any damage observed prior to loading yields an idea of the impact damage dimensions. The plies are numbered 1 to 16; ply No. 1 is in contact with the impactor.

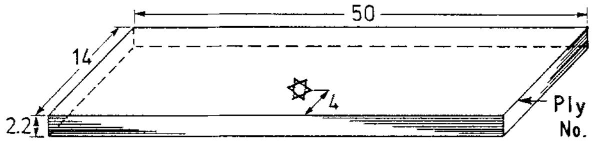

Figure 2 Specimen dimensions and impact location.

The samples are loaded in three-point bending in a Zwick universal testing machine (model 1484) at ambient temperature and at a crosshead speed of 1 mm min^{-1}. The SDR is 8 and the specimen is aligned so as to load ply No. 1 in tension.

3. Results and discussion

The results are divided into mechanical and fractographic analysis.

3.1. Mechanical analysis

3.1.1. Reference specimens

A set of six specimens represent the reference samples strength (RFS). They fail entirely by delamination. Their measured RFS was found to be 56, 57, 58, 60, 66 and 67 MPa. The mean and standard deviation of this group is 61 ± 4.3 MPa. This value agrees with this property mentioned in the literature for CFRP (e.g. [9]).

3.1.2. Impacted specimens

Table I is a summary of all the measured RS values for the various impact parameter values. The maximum number of specimens for each impact conditions is three. The underlined RS values indicate that internal impact damage, which will be discussed later, has been discovered after impact prior to loading. The RS values listed in Table I are plotted versus NOI and energy in Figs 3 and 4. These plots isolate the effect on

TABLE I RS of the various impact parameter values

NOI	Energy (J)			
	2	3	4	5
5	54, 58	41, 56, 58	50, 56, 62	46
15	47, 53	55, 56	43, 56, 58	21 , 43, 45
45	28, 44	46, 47	44, 54	47, 49
135	45	55	48, 35	43
405	49	47	24	39

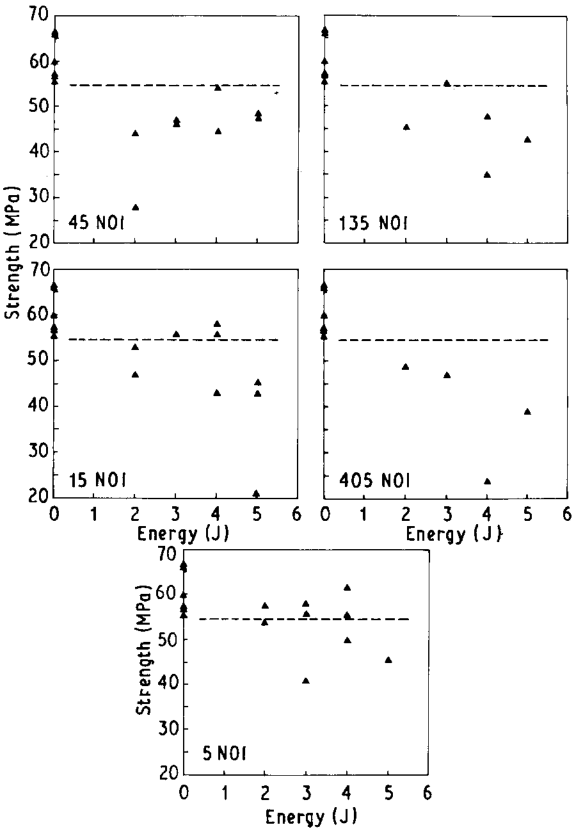

Figure 3 RS versus energy for fixed NOI.

the RS along horizontal lines in Table I, i.e. fixed NOI and different energies (Fig. 3), and along vertical lines, i.e. fixed energy and different NOI (Fig. 4). For highlighting the impact effect on the RS, the RFS values are also plotted. The dashed line in each graph at 54.5 MPa is a reference line positioned at 1.5 standard deviations less than the mean RFS. This value has been selected because it represents a strength for which all the RFS values were above it, i.e. it is below the minimum measured RFS.

In Table II the percentage of specimens having RS > 54.5 MPa (reference line) is listed for each graph in Figs 3 and 4. It is reasonable to consider this percentage as the probability of measuring RS > 54.5 MPa under the present study conditions. Tables I and II and Figs 3 and 4 demonstrates that the RS is widely scattered and there is not a systematic relation between individual impact parameters and the RS. However, it is obvious that almost each parameter separately affects the RS at the energies and NOI which are investigated here. This is emphasized quantitatively in Table II (with the exception of 2 J). From the table it is apparent that as the NOI or energy increases, the probability of RS > 54.5 MPa, decreases, up to the value of 0 at 405 NOI and 5 J.

TABLE II Percentage P of specimens with RS greater than 54.5 MPa for various impact parameters

NOI	P (%)	Energy (J)	P (%)
5	55	2	13
15	40	3	55
45	0	4	36
135	20	5	0
405	0		

The absence of a systematic effect of individual impact parameters can be explained by the low energies and NOI studied here. It is possible that these values are essentially close to the limit for which a detectable effect of impact on this material system is practical. Consequently, a new variable is suggested to overcome the absence of systematic effect of each individual parameter on the RS. This variable is accomplished by a logarithmic combination of the energy and NOI. The definition of this variable is log(NOI × energy). A plot of RFS and RS versus log(NOI × energy) is illustrated in Fig. 5. In addition, the linear regression line of these values is plotted. The correlation coefficient of this linear regression is 63%, which although small is statistically significant. This relation demonstrates that combining the two impact parameters yields a systematic LERI effect on the RS.

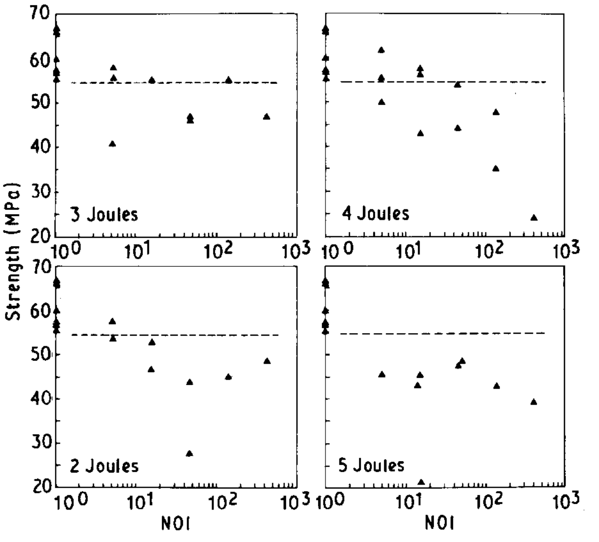

Figure 4 RS versus NOI for fixed energies.

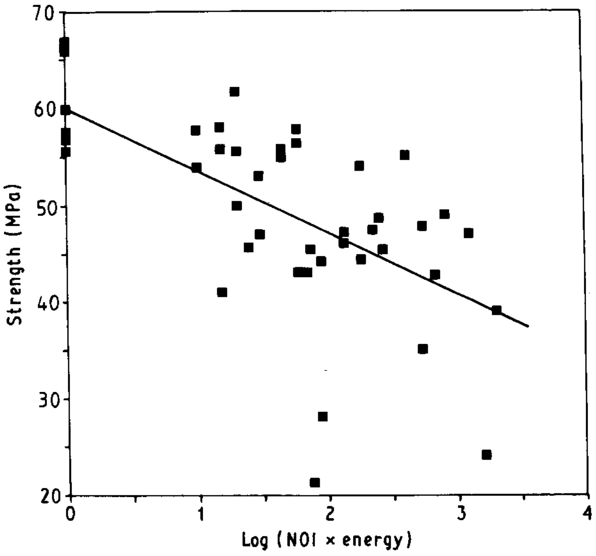

Figure 5 RFS and RS versus log(NOI × energy).

3.2. Fractography

The fractographic study is divided into two categories: external and internal. It is based on characterizing the impact damage and its effect on the failure mode.

3.2.1. External damage

The external damage is examined by visual inspection of the sample surfaces with a light optical microscope. In Fig. 6 a set of typical impact site surfaces of 4 J specimens for 5, 15, and 45 NOI is exhibited. In Fig. 7 a typical set of 5 NOI and 2, 3, 4 and 5 J is displayed. From Figs 6 and 7 it is apparent that

(i) the damage on the surface increases as the NOI or energy increases, and

(ii) despite the fact that the impactor has a spherical shape, the contour of the damage is not circular.

This outcome is because of the sample's unsmoothed surfaces, a result of the manufacturing process.

3.2.2. Internal damage

The internal damage characterization is incorporated by examining the sample's polished through-thickness surfaces once after impact and again after failure. Damage as a result of the impact has been found in two components of the material system; in the plies (i.e. matrix cracking) and in between plies (i.e. delamination). These findings agree with the literature (e.g. [2, 6, 10, 11]). The reference specimens failed by delamination at the interfaces between plies 9 and 10 or 10 and 11. Thus, the "weakest link" in this material with this orientation of plies and under the current loading conditions is at these interfaces.

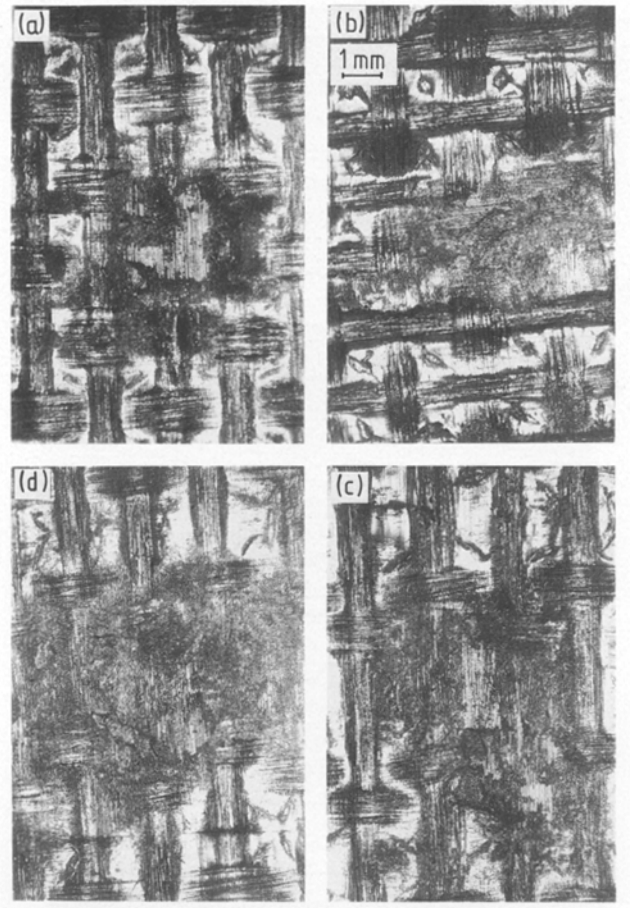

Figure 7 Typical impact specimen surfaces of five impacts and various energies: (a) 2 J, (b) 3 J, (c) 4 J, (d) 5 J.

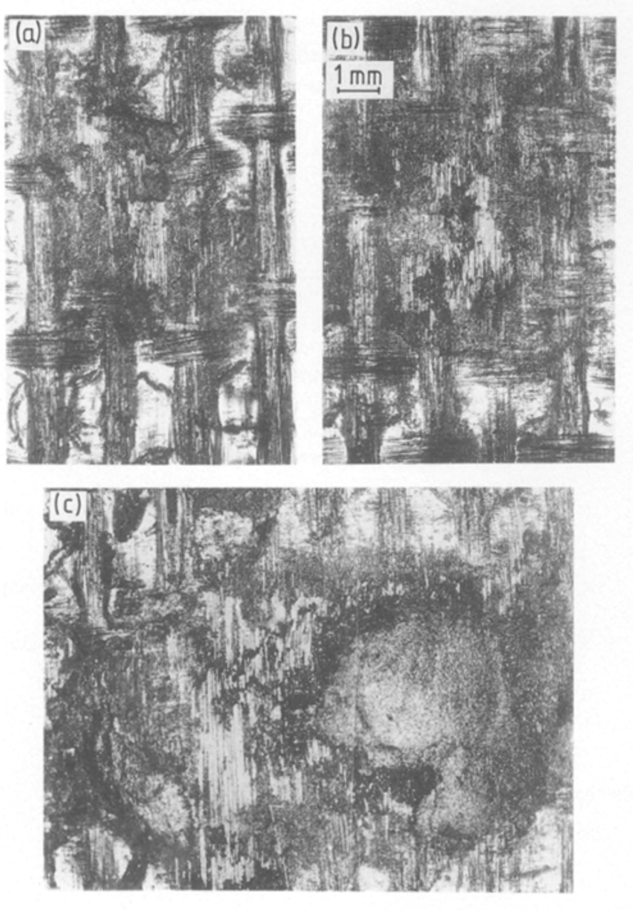

Figure 6 Typical impact specimen surfaces of 4 J and various NOI: (a) 5 impacts, (b) 15 impacts, (c) 45 impacts.

All the impacted specimens were inspected for damage but only in few samples, and without any systematic association with the impact parameters, was damage discovered. The RS values of these samples are underlined in Table I.

In Fig. 8, a picture of a typical sample which possesses impact-damage features of delamination at the 10–11 interface and matrix cracking is shown. In addition, the exact location in the specimen is presented after loading. Due to the damage length, the illustration is cut into three successive pictures. The filled arrows relates to the impact damage prior to loading and the empty arrows to that area in the sample after loading. The impact location is at the right-hand edge of the upper picture. From Fig. 8 it is seen that the damage as a result of impact at the 10–11 interface acts as a source for the final failure, namely delamination at this interface. The RS of this sample was found to be very low, 21 MPa.

In Fig. 9 another specimen is exhibited. Here also, the specimen damage after impact (filled arrows) and after loading (empty arrows) is demonstrated. The impact site is in the middle of the upper picture. The impact damage is at the interfaces 13–14 and 14–15.

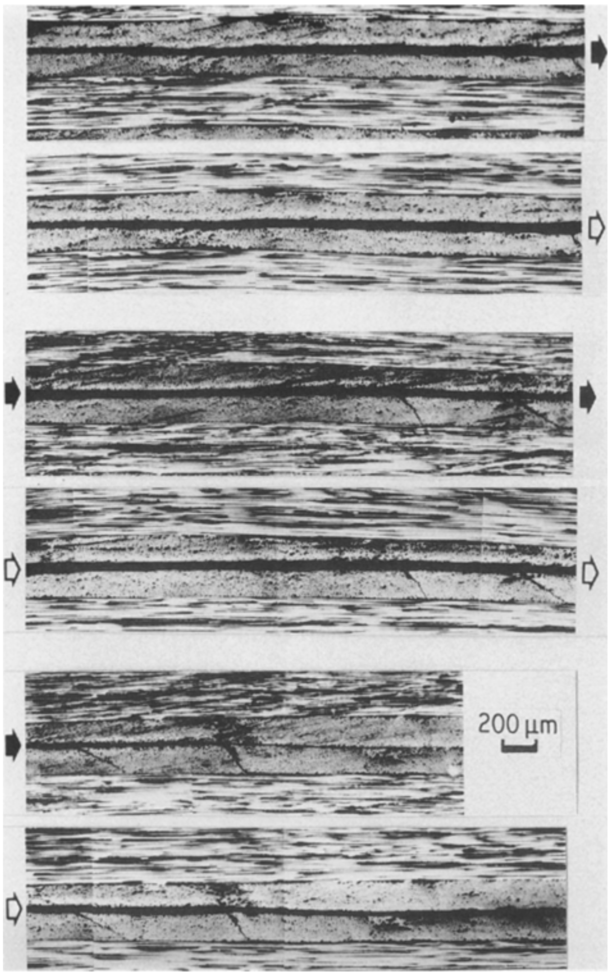

Figure 8 Typical impact damage (filled arrows) and final failure (empty arrows) at interface 9–10.

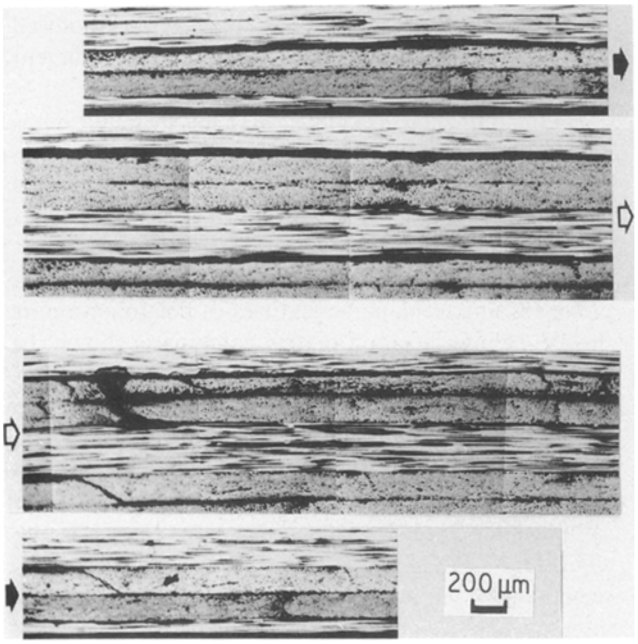

Figure 9 Typical impact damage at interfaces 13–14 and 14–15 (filled arrows) and final failure at interfaces 9–10 and 10–11 (empty arrows).

The loading induced a delamination at the 9–10 interface and no change is discovered at the impact damage site (interfaces 13–14 and 14–15). The interface 9–10, prior to loading, is not shown because no damage has been discovered there at that stage. The RS of this sample was 43 MPa, low compared to the RFS. The RS differences between these two specimens (Figs 8 and 9) is large, possibly due to the position of the impact damage. This shows that the internal location of impact damage is not identical between samples, and the ply/location of impact damage affects the CFRP interlaminar shear strength. If the impact damage is at the "weakest link" of the composite material (interface 9–10 or 10–11), then the RS is low. If the impact damage does not correspond with the "weakest link", the material is not affected to the same degree and the RS is higher, though still significantly lower than the RFS.

4. Conclusions

The effect of LERI on an angle-ply CFRP has been characterized. Low energies, 2–5 J, and up to 405 impacts have been found to affect the interlaminar residual strength of this material system. Each parameter individually does not exhibit a systematic effect on the RS, and in addition the RS suffers from a wide scatter. However, a combination, based on the logarithm of the product of number of impacts with the energy yields a systematic effect on the RS, with low but statistically significant correlation.

Only a few specimens which suffered any internal impact damage at a distance of at least 4 mm from the centre of impact site have been discovered. This shows that even by utilizing small samples, appropriate results can be achieved in low-energy impact research on composites.

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