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A study on the energy dissipation of several different CFRP-based targets completely penetrated by a high velocity projectile

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ABSTRACT

The threat of fragmenting munitions from MANPADS to civilian and military aircraft has, in recent years, become an ever increasing worry. One of the ways to enhance the protection of CFRP based composites is to add lightweight materials that can provide increased ballistic protection. In this study, several hybrid CFRP laminates of different material and geometrical configurations have been subjected to a high velocity steel sphere with an impact energy of c.a. 440 J. It was found that 12 layers of ballistic-grade Kevlar™ loosely bound to the rear of the CFRP laminate proved to be the most weight-efficient method of dissipating the kinetic energy of the projectile. Furthermore, the impact response of a non-woven symmetrical CFRP laminate has been compared to that of a woven laminate over an impact-energy regime of 92 J to 459 J. At lower impact-energies there were strong indications that the non-woven laminate out-performed the woven laminate whereas at the higher impact-energies the ballistic performance was seen to be approximately the same.

Keywords: A. Carbon fibre, **B.** Impact behaviour, **C.** Ballistic penetration, **D.** Energy dissipation

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INTRODUCTION

The terrorist threat to civilian airliners in recent years has become all the more problematic due to the proliferation of MANPADS (man-portable air-defence systems). These systems are capable of launching a missile in the general direction of the aircraft and detonating a fragmenting munition at close proximity to the aircraft's structure. Typically, steel or tungsten fragments are propelled towards the aircraft at high velocity. Although there has been considerable effort to develop countermeasures against such missile systems, these have been deemed prohibitively expensive for commercial airliners [1]. Consequently, there is currently no suitable solution that can provide effective protection against high velocity projectiles produced by a fragmenting munition.

One possibility for improving the survivability of passengers and crew in a civilian airliner is to harden the structure. This is problematic at best due to the increase in weight that would be expected from such a process. However if critical subsystems are sufficiently protected, it may be possible to prevent catastrophic failure of the aircraft when an anti-aircraft munition is detonated in close proximity.

For the foreseeable future, carbon fibre materials will be extensively used in aircraft design [2]. Most high-velocity studies with CFRPs to date have been done using single specimens of relatively thin laminates [e.g. 3-13] that offer very little protection against high velocity projectiles. These studies have shown that these materials have very low trans-laminar strengths and provide very little protection against high energy threats such as a fragment from an anti-aircraft munition. Furthermore, there is a growing body of evidence that suggests that the lay-up type and sequence has little effect on the

performance of a 2D laminate when the material is subjected to a high velocity impact. This appears to be contrary to what has been observed during low velocity impact where woven laminates appear to offer advantages [14-17] and where the stacking sequence has an effect [18]. Hazell et al. [3] have previously reported that small changes in the stacking sequence of a woven laminate had negligible effect on its energy absorbing abilities. Whereas Fujii et al. [4] noted that that there was little difference in the absorbed energy when cross-ply [0/90] laminates were compared to woven laminates. Furthermore, Tanabe et al. [5] also showed no difference in energy absorption between cross-ply and woven laminates. Hammond et al. [7] showed that thin laminates of different quasi-isotropic lay-ups did exhibit a difference in energy absorption. However, they noted that the measured difference was small and was well within their experimental error. However, they also pointed out that unidirectional composites were significantly weaker than the other lay-ups. Interestingly, Lopez-Puente et al. [19] have studied the effect of low temperature on the impact response of CFRP laminates. They showed that quasi-isotropic tape laminates were less effective in terms of residual damage than woven laminates due to the different flexural behaviour of the plies. However no residual velocity was measured in this instance. They also showed that temperature has no effect on damage extension implying that the energy absorbing characteristics at room temperature are similar to that at lower temperatures experienced by high altitude aircraft.

There does, however, appear to be an effect on the material's energy absorbing ability with changing the type of fibre – particularly on the rear surface of the laminate. Tanabe et al. [5] have shown that small differences in ballistic performance are possible if carbon fibres of different properties are used in the through-thickness of the sample.

They concluded that high tensile strength fibres should be used on the rear surface of the laminate to maximise energy absorption of the projectile. Similar observations were made by Fujii et al. [4]. They also showed that failure modes were affected by the mechanical properties of the fibre. Laminates with low strength carbon fibres resulted in specimens showing plugging-type fractures.

Lamontagne et al. [20,21] have studied the penetration of CFRP laminates at oblique angles; however, this was done at very high velocities that far exceed the velocities of fragments that would be encountered by an aircraft structure. Here, the main focus was on the response of space-craft structures to high velocity impact. Further high velocity impact studies on CFRP-based space-craft structural materials have been conducted by Ryan et al. [22] and White et al. [23]. In these papers the authors turned their attention to the high velocity impact response of hybrid CFRP laminates consisting of either Kevlar layers or aluminium honeycomb bonded directly to CFRP laminates. It was reported in [23] that the presence of Kevlar-epoxy layers reduced the extent of delamination and increased the impact energy required to induce rear surface damage. Again, in this work, the velocities of impact far exceeded those of interest in this paper. Nevertheless, Kevlar is a composite material that is well known for its ballistic properties as are certain grades of aluminium alloy [24].

Most work to date has concentrated on very thin laminates (c.a. 2 mm) comparing the ballistic performance of different quasi-isotropic lay-ups or comparing cross-ply [0/90] with woven laminates. In this work we evaluate the ballistic performance of a relatively thick symmetrical non-woven laminate over an impact energy-regime ranging from 92 J to 459 J and compare it to a similar woven laminate subjected to impact by

similar loading conditions [3]. Further we evaluate the energy dissipation and consequent improvement in ballistic performance by adding Kevlar and aluminium layers to this laminate in an attempt to show how the ballistic performance of these materials can be improved.

EXPERIMENTAL METHODOLOGY

Materials used

The materials chosen for this study were manufactured using the resin transfer method (RTM). All individual panels were manufactured with Tenax HTS 5361 aero grade fibres and chosen because they are commonly used in the aerospace industry. The lay-up consisted of 10 plys: $[0/90, \pm 45, 0/90, \pm 45, 0/90]_s$. The thickness of each CFRP panel was 5.30 mm ± 0.05 mm. The resin used was Hexcel RTM 6 cured for 1 hour 40 minutes at 180 °C and at a pressure of 90 psi. The dynamic behaviour of the cured resin has previously been studied in [25]. The density of the CFRP material, measured using a Micrometrics AccuPyc 1330 gas pycnometer, was 1.53 g/cc ± 0.01 g/cc. The mass fraction of the reinforcement was measured using the acid digestion method according to ASTM D 3171-6, Procedure B [26] and was found to be 70.3±1.0%.

Two additional materials were also used to construct the hybrid laminates. These were Dural (Al 6061-T6) of thickness 1.02 mm ± 0.01 mm and plain-weave Kevlar™ 29 fabric manufactured by DuPont (USA) with a yarn linear density of 1500 denier and a

tow count of 324 tows/square inch. Twelve layers of Kevlar fabric was chosen to match the areal density of the Al6061-T6 (2.8 kg/m^2).

Target construction

The hybrid CFRP laminates were assembled by roughening the surface of each component and applying a two-part epoxy adhesive (Araldite 2015) to bond the layers together under load. Eleven different targets were constructed as summarised in Figure 1 and Table 1. Two different bonding approaches were used for the Kevlar fabric. One set of targets were assembled by just bonding around the periphery of the target (Configurations H, I and J); a target was assembled by completely bonding the surfaces of each respective Kevlar layer to its neighbour (Configuration K).

Figure 1: NEAR HERE.

Impact testing

The projectile used was a fully annealed stainless steel sphere (∅11.97 mm ± 0.01 mm; mass = 7.165 g ± 0.001 g; VHN = 127). The balls (AISI 304) were fully annealed in air at 1050°C to provide equiaxed austenite grains and consequently isotropic behavior. The yield strength of this steel at 21°C is 450 MPa with an ultimate tensile strength of 675 MPa [27]. The projectile was fired from ELVIS, a single stage ∅22-mm gas-gun. The impact energy ranged from 92 J – 459 J corresponding to a velocity range of 160 m/s

to 358 m/s. This range of velocities is lower than what would be expected from the majority of fragments propelled from an anti-aircraft munition. Nevertheless, anti-aircraft munitions provide a spread of fragments with a distribution of velocities and this velocity range would be representative of some of the propelled fragments. Furthermore, this velocity range is consistent with that of debris that may be propelled from the runway to the underside of an aircraft during take-off and landing [e.g. 28-30]. Target specimens were cut from the bonded panels into 150 mm × 150 mm squares and secured at the top and bottom using the target holder shown schematically in Figure 2.

Both impact and exit velocities were measured using a high speed video camera (Phantom 7; 20,000 frames per second; 2 μs exposure time). The energy transferred to the panel was assessed by measuring the impact velocity and the residual velocity of the projectile to an accuracy of <1 %. The energy transferred to the target (E_t) was calculated from

$$E_t = \frac{1}{2} m_p \left(v_i^2 - v_r^2 \right) \qquad (1)$$

where m_p is the mass of the projectile, and v_i and v_r are the impact and residual velocities.

Consequently, the percentage change in kinetic energy (ΔE_f) was calculated using

$$\Delta E_f = \frac{E_t}{E_i} \times 100 \qquad (2)$$

where E_i is the kinetic energy of the projectile prior to impact.

Figure 2: NEAR HERE.

RESULTS AND DISCUSSION

The response of the CFRP laminate alone (Configurations A and B)

The change in the kinetic energy (KE) for the single bare CFRP laminates (without any additional materials) is shown below in Figure 3. Results from similar impact tests on a slightly thicker woven laminate (5HS) from [3] are also included for comparison. In both cases, a rapid drop-off in the percentage of impact energy dissipated by the plate is apparent as the impact energy is increased. Both sets of results show that the percentage of energy dissipated by the laminate appears to approach an asymptotic level. Further studies reported in [12] revealed that the asymptotic level for the 6-mm thick 5HS woven laminate was indeed reached at an impact energy of 2000 J with a percentage energy absorption of 20 %.

In two cases the sphere did not completely penetrate the composite laminate. At an impact energy of 105 J the sphere became completely embedded, whereas at an impact energy of 92 J it rebounded, resulting in a lower percentage of energy being dissipated. It is notable that at the higher impact energies (>130 J) this CFRP laminate appeared to perform less-well than the 5HS woven laminate tested in [3]. The slightly poorer performance is, perhaps, expected due to the lower thickness tested here. However, when compared at an impact energy of c.a. 440 J the percentage of kinetic energy dissipated by

the laminate, normalised by the thickness, is very similar (5.4 %/mm). Consequently, these results imply that at the higher impact energies at least, our findings are similar to the findings of Fujii et al. [4] and Tanabe et al. [5]. They showed that there was no difference in the ballistic performance of a laminate regardless of lay-up. However, at an impact energy of c.a. 120 J, the non woven laminate tested dissipated the same amount of kinetic energy as the thicker woven laminate tested in [3]. Indeed, extrapolation of the woven laminate result in Figure 3 suggests that the thinner non-woven laminate performed better than the woven laminate at the lower impact energies. Although the differences do appear small, our results show that there are differences in the energy absorbing ability between the two types of laminates at the lower impact energies with the non woven laminate performing better.

Also included in Figure 3 are two shots that were conducted on the two-part bonded CFRP laminates. At an impact energy of 245 J (261 m/s), the projectile became fully lodged in the laminate and consequently the system completely absorbed all of the kinetic energy of the projectile. Increasing the impact energy to 436 J (349 m/s) resulted in perforation. Nevertheless, a considerable amount of energy was dissipated by this relatively thick laminate (77 %). This corresponded to a percentage of impact energy-per-unit-thickness of 7.1 %/mm. For this given impact energy (c.a. 440 J), this implies that the double-bonded laminates are more efficient at resisting penetration (per unit thickness) than the single laminates. This has been previously been seen with 5HS woven laminate constructions [31].

Figure 3: NEAR HERE.

The response of the single CFRP laminate that completely stopped the projectile with an impact energy of 105 J is shown in Figure 4. It should be noted that the high-speed video actually captured a frame every 50 μs. However, in order to illustrate the nature of the impact a minimum interval of 100 μs is chosen in this case. Here the reference time (0 μs) is arbitrary and occurs when the projectile is 6.8 mm from the target face. By 200 μs, the projectile was completely embedded in the laminate; by 3100 μs the projectile is completely at rest and ejection of the rear-surface tows is seen. It can be seen that at 100 μs, the laminate has been subjected to flexure prior to some of the tows being ejected; in this case, only the final layer of tows (running into the paper) are ejected.

Figure 4: NEAR HERE

As shown in Figure 5, increasing the impact energy to 211 J (243 m/s) results in a more catastrophic failure as the projectile completely penetrates the CFRP laminate. There are a few things to note here. Firstly, by 50 μs penetration of the target has begun and dishing is seen to occur at the rear of the target. Secondly, by 100 μs failure of the longitudinal tows is seen to occur as the dishing of the rear surface continues before; thirdly, the rear tows break away from the rear surface at 150 μs. By 250 μs, the projectile is clearly seen emerging from the target with a kinetic energy of 115 J (179 m/s).

Figure 5: NEAR HERE

With this composite, the final layers of the carbon fibres appeared to have failed in tension. This behaviour is different from the penetration mechanism of the 6-mm woven RTM composite as seen in [3]. In this case, it was noted that at a higher impact velocity (305 m/s) dishing preceded the formation of a plug of CFRP laminate inferring that a compression / shearing mechanisms had occurred. It should be pointed out that in the course of the study of this particular laminate the formation of a plug of CFRP material was not observed. Previously, other researchers have observed plug formation during the penetration of CFRP materials. Li and Sun [32] noted plug formation in thin CFRP laminates that had been struck by a blunt-ended projectile at relatively low velocities (<100 m/s). Further, Cantwell and Morton [8] have previously shown that during the perforation of a thin CFRP material, a frustum–shaped fracture zone is formed. This observation is consistent with the conically shaped plugs that were soft-captured in [3].

The response of adding aluminium layers (Configurations C-F)

The ballistic performance of the aluminium-based laminates when perforated is summarised in Figure 6. In each case, the impact velocity of the sphere was c.a. 350 m/s – the maximum velocity attainable by the gun used in this experimental programme and corresponding to an impact energy of c.a. 438 J. This velocity of impact resulted in a percentage of impact energy dissipated by the bear CFRP laminate of c.a. 30% which is close to the level of absorption expected from single laminates subjected to much higher impact velocities [12]. Also included in Figure 6 are the level of energy dissipated by both a two-part bonded CFRP laminate and single laminate for comparison.

Figure 6: NEAR HERE

As can be seen from Figure 6, c.a. 90 % of the projectiles KE was dissipated by the two-part bonded CFRP panel that included a Dural interlayer (configuration C). This out performed the two-part bonded CFRP laminate (shown by the arrow). However, it should be pointed out that although this system appeared relatively efficient, its areal density was considerably higher than the other systems tested (see Table 1).

Placing a single thin layer of Dural on either the front or the rear surface appeared to improve the energy dissipation. The configuration with the aluminium on the rear layer (configuration F) appeared to dissipate slightly more projectile kinetic energy than that of the configuration consisting of the layer on the front (configuration E). This is most probably due to the fact that during penetration, the rear-layered target was able to dish quite considerably before petalling (see Figure 7) and consequently expend further energy in the process (see Figure 8). Combining a Dural layer on the front and rear surfaces of the CFRP laminate led to a percentage of KE absorbed of c.a. 70 %. Consequently the additional percentage energy absorbed was 42 % due to the addition of the two layers when compared to the bare CFRP laminate. This value was similar to the combined benefit of individually adding a front layer (20 %) and a rear layer (23 %) to the CFRP implying that the two-layered system conveyed no additional systemic advantage. That is, its energy absorption ability was not greater than that of the sum of its individual parts.

Figure 7: NEAR HERE

Figure 8: NEAR HERE

The response of adding Kevlar layers (Configurations G-K)

The effect on the energy dissipation of the projectile by adding the Kevlar layers is shown below in Figure 9. Again, in each case, the impact energy of the sphere was c.a. 440 J.

Figure 9: NEAR HERE

Here, the two-part bonded CFRP laminate with the Kevlar layer in-between (configuration G) outperforms the equivalent aluminium system (configuration C, shown in Figure 6). At this velocity, the system manages to defeat the projectile – completely dissipating its kinetic energy. Adding the loose Kevlar layers to the rear of the CFRP laminate resulted in a considerable improvement in performance of the system over and above the fully bonded layers. Cheeseman and Bogetti [33] have noted that weak fibre-matrix adhesion is desirable as this allows for fibre stretching. This results in the ready delamination of the fabric, which allows the fibres to extend to failure and thereby facilitating further energy expenditure. Figure 10 shows selected high speed video footage of the steel sphere striking a CFRP laminate backed by 12 layers of Kevlar (configuration J); the impact energy was 444 J. In this case, the Kevlar fabric is bonded

around the periphery of the target only. It is evident that extensive deformation of the target is occurring during the penetration resulting in, this case, a relatively high level of energy dissipation. Consequently, our results are consistent with Cheesman and Bogetti's observation. Attaching layers of Kevlar on the front face of the CFRP resulted in 45% of the projectile's kinetic energy being dissipated -- similar to the aluminium-faced CFRP. In these cases, the presence of the CFRP laminate behind the reinforcing material probably restricted the degree of deformation or fibre stretching thereby minimising the energy absorption. Indeed, there was little sign of weave disruption close to the impact site of the Kevlar-faced target.

Figure 10: NEAR HERE

Analysis of the areal densities

Below in Figure 11 we have plotted a performance map for each of the samples tested in this experimental programme. We have assumed a linear behaviour in the percentage of energy absorbed as the areal density of the CFRP increases from 8.1 kg/m^2 to 16.2 kg/m^2. Consequently, a straight line is plotted through the results for samples A and B. By implication, any results to the right of the line indicate a ballistic performance where the additional material has a detrimental effect on the system's performance (from a weight point-of-view). Conversely, any results to the left of the line show that the additional material provides a benefit to the overall system. There are a few things to note from these results. Firstly, it is notable that, apart from one case, the Kevlar-based targets

performed considerably better than the aluminium-based targets (configurations C-F). This perhaps, is expected given the known energy absorbing ability of woven aramid fabrics [33,34]. There is one notable exception in configuration I where the 12 layers of the Kevlar on the front surface bestow little-to-no advantage over a bare CFRP laminate. Furthermore, rear-faced Kevlar performs better than placing layers on the front and the back – from a weight performance criterion. Secondly, configuration C is the only sample to fall to the right of the straight line. Although we note that the difference is small, the reduced performance of this target can be explained by sandwiching of the Dural in-between the CFRP laminates. Consequently, dishing (and energy absorption) was inhibited during penetration. Thirdly, the addition of aluminium faces either to one or both faces of the target (configurations D-F) led to only a small increase in ballistic performance of the system when the additional weight was taken into account.

These results show that a significant increase in energy absorbing ability is best achieved by fixing loose woven aramid fibres to the rear of the CFRP laminate.

Figure 11: NEAR HERE

CONCLUSIONS

A series of high velocity impact tests have been carried out on a symmetrical non-woven CFRP laminate and a variety of hybrid CFRP sandwich panels. The first objective of this work was to evaluate the ballistic performance of a relatively thick non-woven laminate over an impact energy-regime ranging from 92 J to 459 J and compare it to a

similar woven laminate subjected to impact by similar loading conditions. The second objective of this was work was to evaluate the energy dissipation and quantify the improvement in ballistic performance by adding Kevlar and aluminium layers to the CFRP. This work has shown that:

(1) Although the ballistic performance as measured per-unit-thickness was similar to an RTM-based woven structure at the high impact energies, there are strong indications that at the lower impact energies, the non-woven sample tested here out-performed the woven sample.

(2) Adding 12 layers of ballistic grade Kevlar™ loosely bound to the rear of the CFRP laminate performed considerably better than other similar weighted configurations including the use of Dural. Indeed we have found that for an impact-energy of c.a. 440 J, 93 % of the projectile's kinetic energy was dissipated as opposed to 77 % that can be achieved by bonding a second CFRP laminate of equal thickness to the target laminate.

(3) Placing layers in-between two CFRP laminates, where the main mechanism of energy absorption is through inelastic deformation due to dishing, results in a reduced ballistic performance when weight is taken into account.

(4) The addition of Kevlar to the front surface of the CFRP laminates resulted in little-to-no improvement to the ballistic performance of the system by virtue of the fact that the CFRP laminate appeared to restrict fibre extension.

Overall it is apparent from this study that significant measurable improvements in ballistic performance of CFRP-based structures can be introduced for only c.a. 25 % increase in areal density.

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FIGURE CAPTIONS

Figure 1: Target construction.

Figure 2: Experimental set-up for the high velocity shots.

Figure 3: Percentage change in KE due to the perforation of the CFRP laminate at different impact energies.

Figure 4: Selected high-speed video frames showing the impact of a 12 mm steel sphere on the 5.3-mm thick CFRP laminate (configuration A) at 171 m/s (105 J); the circle shows projectile capture.

Figure 5: Selected high-speed video frames showing the impact of a 12 mm steel sphere on a 5.3-mm thick CFRP laminate (configuration A); impact energy = 211 J (243 m/s).

Figure 6: Energy dissipated by the aluminium-based CFRP laminates.

Figure 7: Selected high-speed video frames showing the impact of a 12 mm steel sphere on a 5.3-mm thick CFRP backed by 1 mm of Dural (configuration F); impact energy = 448 J (354 m/s).

Figure 8: Rear Dural layer from an experiment (configuration E) showing evidence of dishing and petalling.

Figure 9: Energy dissipated by the Kevlar-based laminates.

Figure 10: Selected high-speed video frames showing the impact of a 12mm steel sphere on a 6mm thick CFRP backed by 12 layers of Kevlar (configuration J); impact energy = 444 J (352 m/s).

Figure 11: Performance graph for each of the specimens tested in this experimental programme; in each case the impact energy was c.a. 440 J.

Table 1: Target construction summary

Configuration	Description	Areal density (kg/m^2)
A	A single CFRP laminate	8.1
B	Two CFRP layers bonded together	16.2
C	A Dural layer sandwiched in-between two CFRP layers	19.0
D	CFRP sandwiched in-between two Dural layers	13.7
E	Dural (impact face) bonded to CFRP	10.9
F	CFRP (impact face) bonded to Dural	10.9
G	A Kevlar lay-up sandwiched in-between two CFRP layers	19.0
H	CFRP sandwiched in-between two Kevlar layups (bond around the periphery of the target)	13.7
I	Kevlar (impact face) bonded to CFRP (bond around the periphery of the target)	10.9
J	CFRP (impact face) bonded to Kevlar (bond around the periphery of the target)	10.9
K	CFRP (impact face) bonded to Kevlar (bond completely covering the surface)	10.9

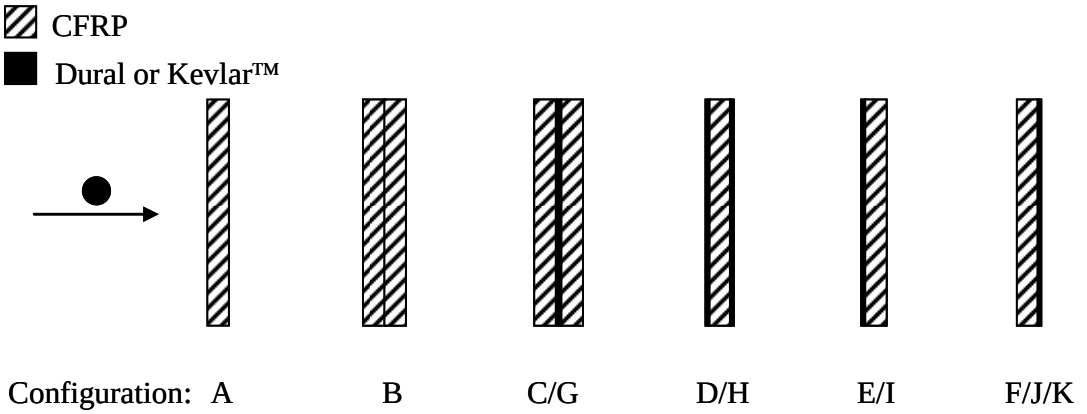

Figure 1

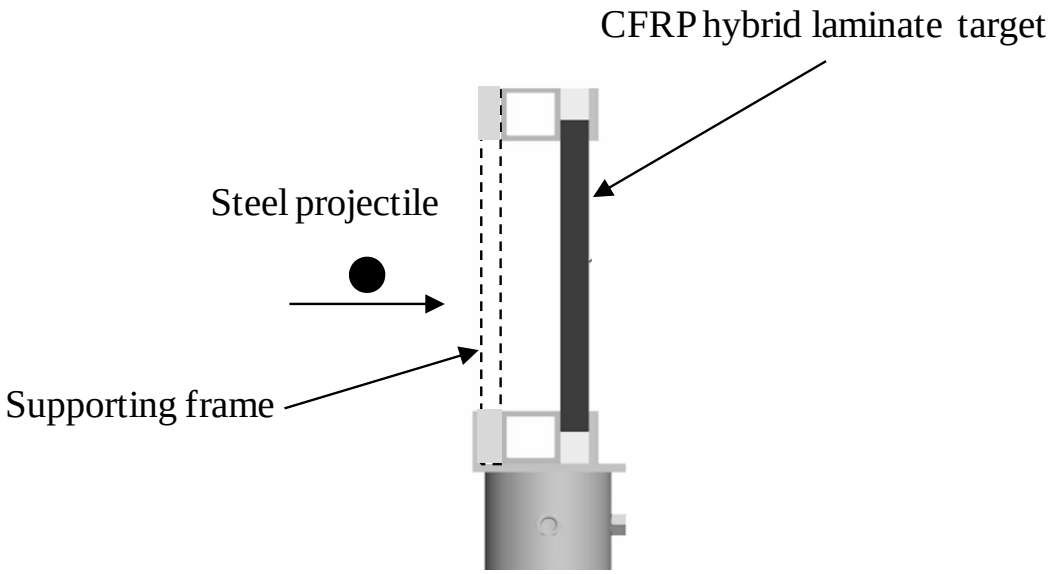
CFRP hybrid laminate target
Steel projectile
Supporting frame

Figure 2

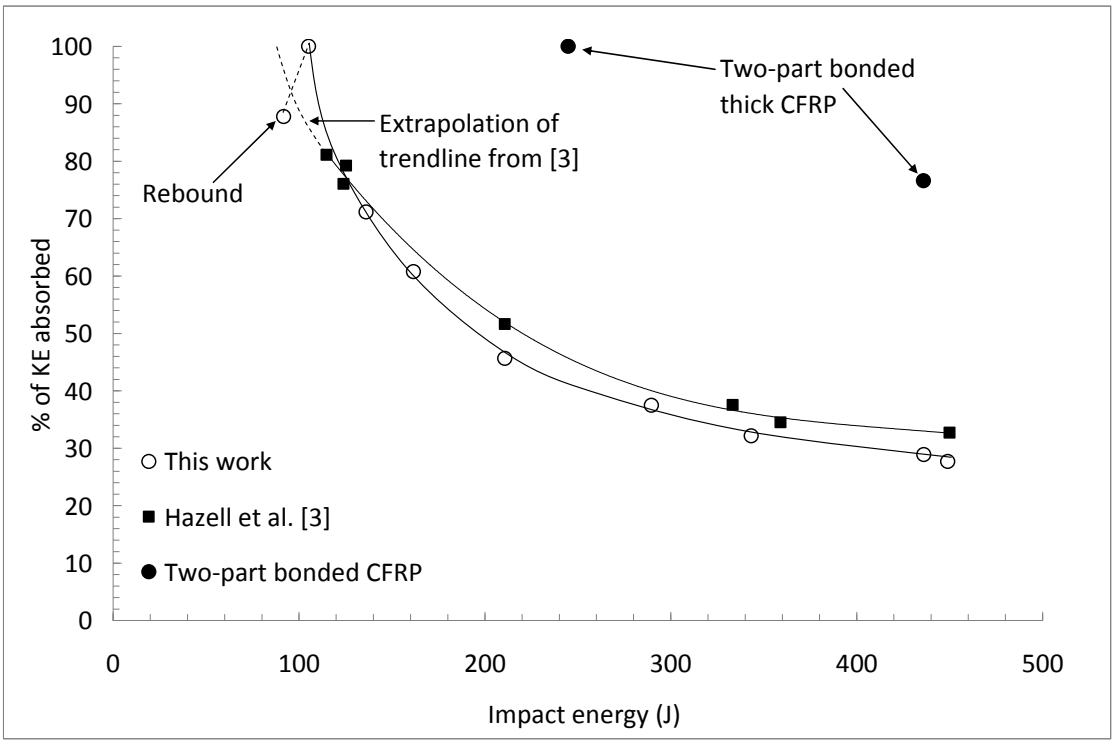
100
90
80
70
60
50
40
30
20
10
0
% of KE absorbed
0
100
200
300
400
500
Impact energy (J)
Two-part bonded
thick CFRP
Extrapolation of
trendline from [3]
Rebound
This work
Hazell et al. [3]
Two-part bonded CFRP

Figure 3

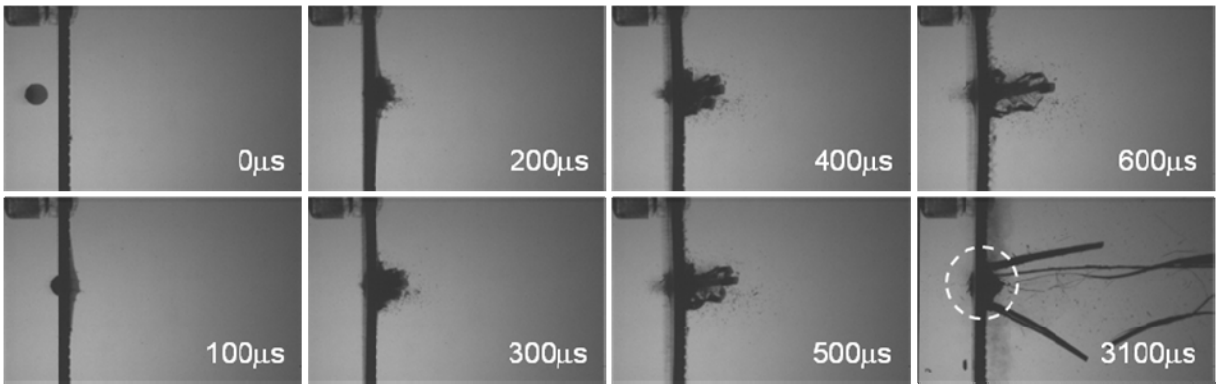

Figure 4

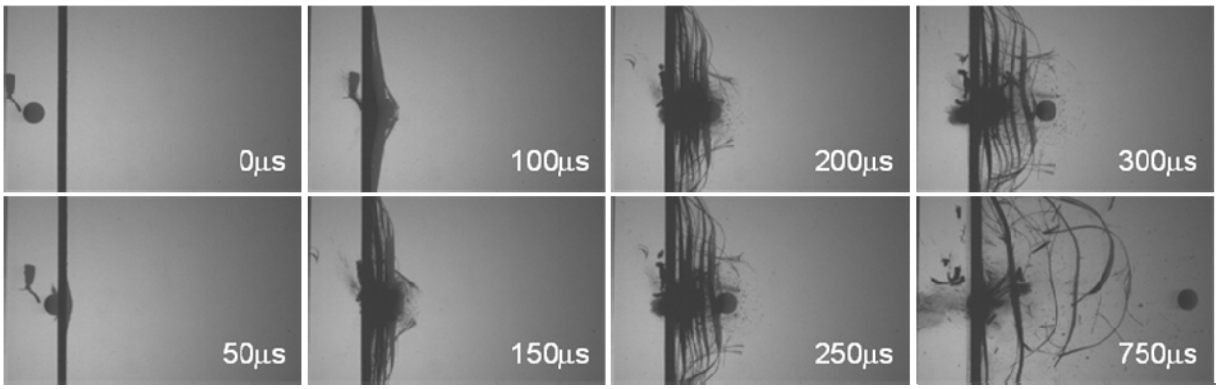

Figure 5

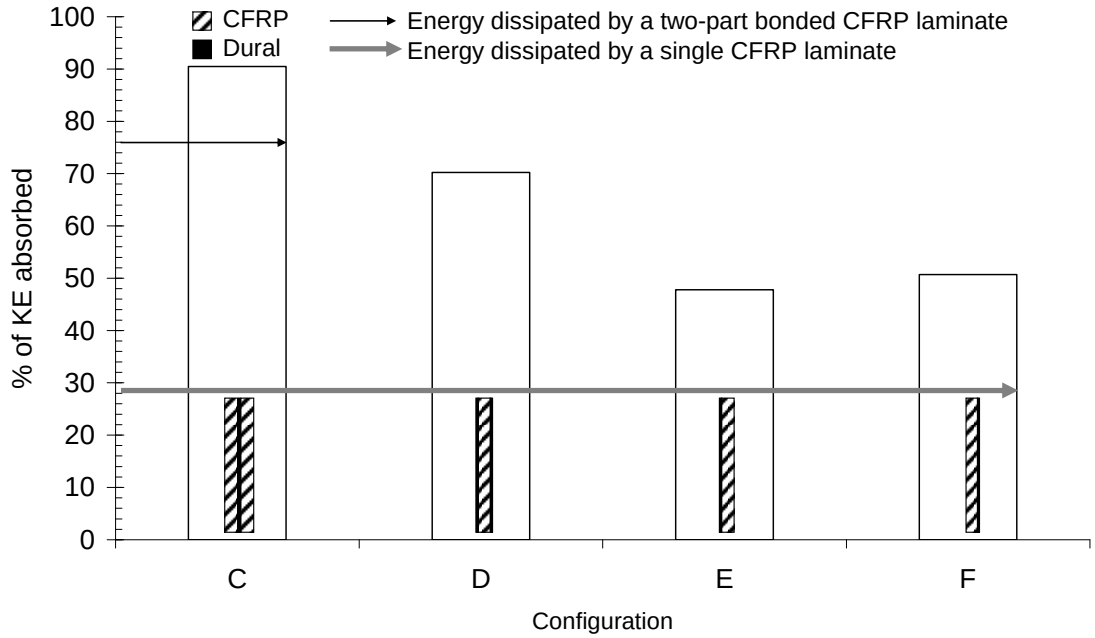
100
90
80
70
60
50
40
30
20
10
0
% of KE absorbed
CFRP
Dural
Energy dissipated by a two-part bonded CFRP laminate
Energy dissipated by a single CFRP laminate
C
D
E
F
Configuration

Figure 6

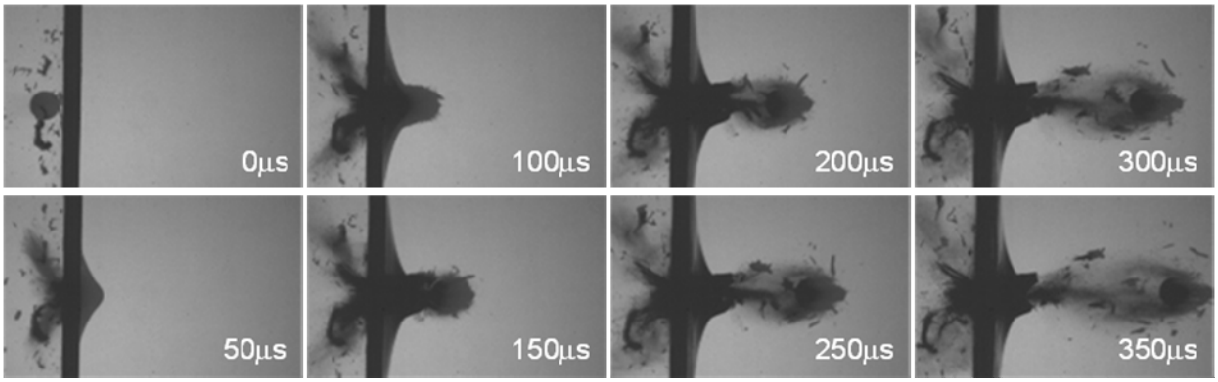

Figure 7

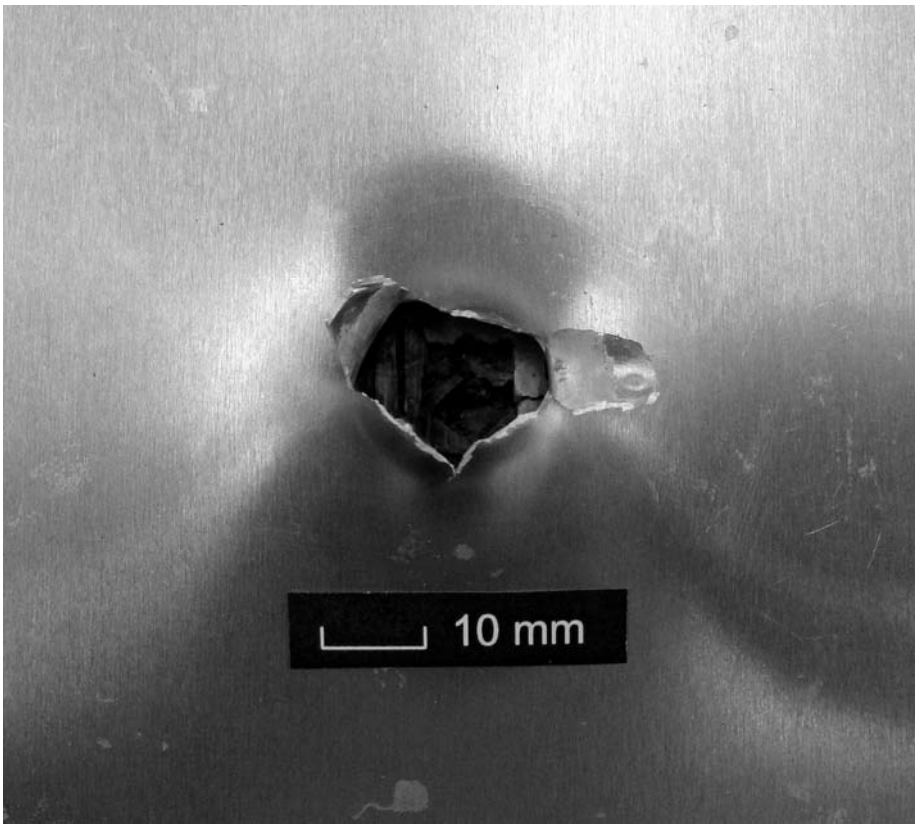

Figure 8

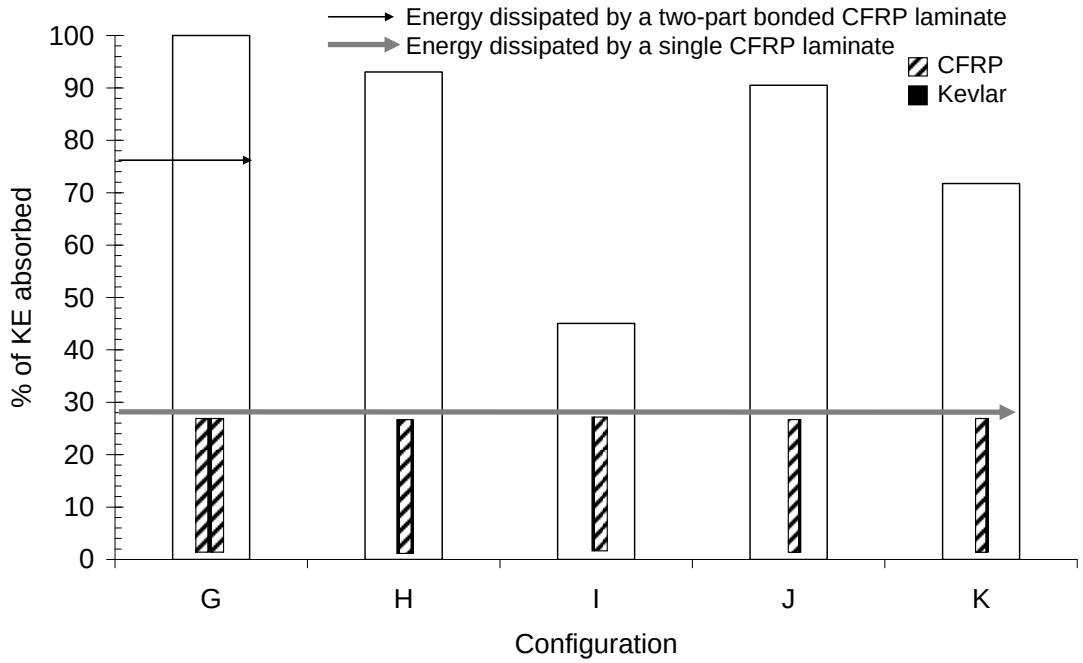
Energy dissipated by a two-part bonded CFRP laminate
Energy dissipated by a single CFRP laminate
CFRP
Kevlar
% of KE absorbed
100
90
80
70
60
50
40
30
20
10
0
G
H
I
J
K
Configuration

Figure 9

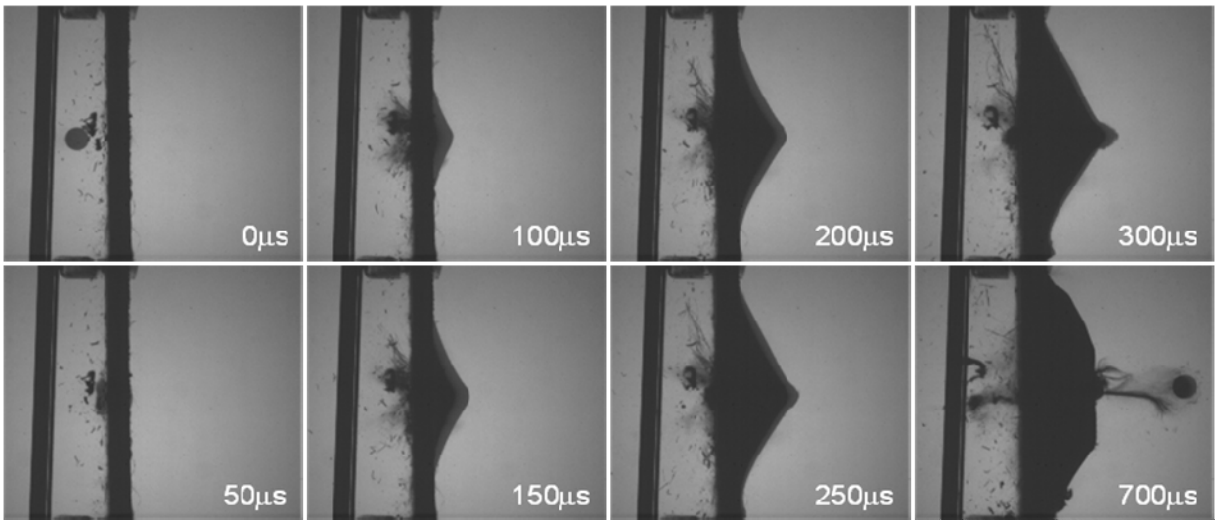

Figure 10

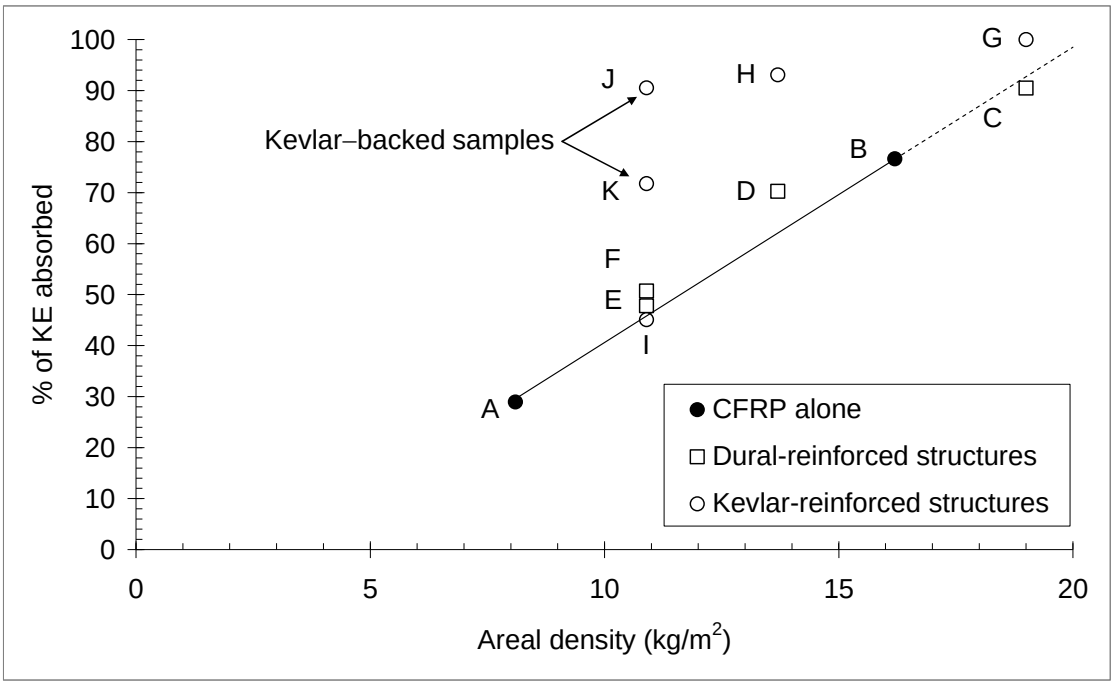
100
90
80
70
60
50
40
30
20
10
0
% of KE absorbed
0
5
10
15
20
Areal density (kg/m2)
Kevlar–backed samples
A
B
C
D
E
F
G
H
I
J
K
CFRP alone
Dural-reinforced structures
Kevlar-reinforced structures

Figure 11

https://dspace.org/

A study on the energy dissipation of several different CFRP-based targets completely penetrated by a high velocity projectile

Hazell, Paul J.; Appleby-Thomas, Gareth J.

2009-12-31T00:00:00Z
Elsevier
https://doi.org/10.1016/j.compstruct.2009.04.036

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