# PREFERENTIAL ENERGY ABSORBING INTERFACES FOR BALLISTIC AND STRUCTURAL APPLICATIONS

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**Keywords***:* ballistic performance, hybrid sizing, interlaminar toughness, shear strength, fibre sizing

## 1 Summary

The ballistic performance of “smart-sized” S2-glass fibre reinforced epoxy was evaluated in comparison with matrix compatible, matrix semi-compatible and matrix incompatible sized materials. The smart size is a formulation designed to give rate-dependent behaviour.

The smart-sized material was shown to exhibit rate dependent changes in interlaminar shear strength and mode I interlaminar fracture toughness testing; the ballistic performance of the material was improved only slightly over compatible sized materials. This is attributed to reduced fibre tensile strength in the smart-sized fibres, which was a competing effect, limiting energy absorption during ballistic impact. Overcoming the fibre strength degradations, which appears to be caused by frictional handling effects, is likely to result in significant improvement in ballistic limit. A hybrid laminate consisting of interleaved plies of the compatible and incompatible sizings described above showed synergistic improvements to ballistic performance above what might be expected through rule of mixtures when incompatible sized plies were located towards the rear of the laminate.

## 2 Introduction

The requirement of rapid response in modern conflicts necessitates lower mass solutions for future armoured vehicles and fibre reinforced polymer composites offer a potential solution. During ballistic impact, fibre-composites absorb energy through a combination of frictional sliding, fibre debonding, matrix cracking/delamination and fibre fracture mechanisms [1]. It has been observed that ballistic performance is improved in composites with weak fibre matrix interfaces whilst residual compression and flexural strength are improved in composites with stronger fibre/matrix interfaces [2]. The strength of the fibre/matrix bond is controlled primarily by receptor-sticker group interactions. Maximum interfacial strength occurs at an optimum number of surface interactions which has been shown to vary with temperature such that more interactions are required at lower temperatures [3].

Due to the time-temperature equivalence behaviour in polymeric materials, it is conceivable that the adhesion behaviour may also be rate dependent. Using a combination of matrix compatible and matrix incompatible silane coupling agents to create a ‘mixed’ glass fibre sizing, Jensen and McKnight [4] tested the resulting composite materials using drop-weight testing and compared the results with those from glass fibre composite materials with fully matrix compatible or matrix incompatible sizings. They observed that the peak load experienced by specimens using the ‘mixed’ sizing was higher than both fully compatible and incompatible sized materials. In addition, the maximum energy absorption of the mixed sizing material was shown to be increased with respect to fully compatible sized specimens, although the mixed sizing material still showed substantially lower energy absorption compared with the fully incompatible sized material. The peak load can be considered indicative of structural performance, whilst the energy absorbed during the impact indicates the potential ballistic performance of the materials [4]. In order to increase energy absorption through frictional mechanisms such as fibre pull-out a fourth ‘hybrid’ sized material consisted of the ‘mixed’ sizing combined with a colloidal silica fibre surface roughening agent; this material showed substantial improvement in both maximum load and maximum energy absorbed with respect to the other three sizings [4].

In the present study, ballistic testing of an epoxy matrix composite reinforced with the hybrid sized S2-glass fibre was compared with fully matrix compatible, semi-compatible and incompatible sized materials. These results have been correlated with interlaminar shear strength and mode I interlaminar fracture tests which were carried out at quasi-static, intermediate and high loading rates in order to assess the mechanisms that most directly affect ballistic performance.

## 3 Materials

S2 glass fibres were obtained from AGY Inc with fibre sizings ranging from epoxy compatible (463) and semi-compatible (365) to incompatible starch oil (636) and the “smart” rate sensitive sizing (ARL). The compatible sizings (463 and 365) are surface additive treatments used to strengthen the bond at the fibre matrix interface and protect the glass fibre during processing. Silane is a common choice that chemically bonds to the glass and matrix materials to increase adhesion.

The incompatible 636 starch oil system is applied to the fibre for the purpose of subsequent weaving processes. The oil based size inhibits adhesion, reducing structural performance. This has been recognised as being advantageous to impact performance since it allows for greater energy absorption through fibre pullout and fibre matrix debonding [1].

The ARL size (described above as the ‘smart’ sizing) has been developed to promote strong interfacial strengths under static load conditions; for higher rate impact events, the sizing exhibits a switch of behaviour resulting in reduced interfacial strength.

In all cases where the fibres were utilised in laminate form, the panels were constructed from unidirectional prepreg using MTM49 epoxy resin. The increased surface roughness of the ARL sized fibres resulted in complications to the commercial prepregging process and as a consequence an alternative, in-house production method was adopted involving the winding of dry fibre onto an MTM49 epoxy film over a cylindrical drum. This was then followed by a consolidation stage to assist the infiltration of the epoxy between fibres. This method produced pre-preg of identical weight and volume fraction to the commercial prepreg, however the spreading of the fibre yarn was not as uniform.

## 4 Experimental Methods

### 4.1 Single fibre tension tests

Single fibre strength tests were carried out in the usual way. Individual fibres were carefully separated from a tow of dry fibre and placed across a card with a rectangular window 30 mm in length. The fibre was attached to the card at the edges of this window using an epoxy adhesive. Each specimen was checked individually using reflected light optical microscopy to verify that only a single fibre was present.

Subsequently the cards were gripped within an Instron 4507 testing machine with a 10 N load cell then the cards were cut leaving the fibre unsupported within the test fixture. Load was applied to the fibre at a constant displacement rate of 1 mm/min until the fibre was broken. Failure loads were recorded and the location of the fibre failure (within the gauge length or at the point of adhesion) was noted.

### 4.2 Interlaminar shear strength

Double notch shear tests were used to measure the interlaminar shear strength (ILSS) of composite laminates following ASTM Standard C1292 [7]. ILSS is dependent on matrix and interface performance and structural composite laminates usually show high shear strengths. In addition to affecting the static load carrying capability of the composite, ILSS is relevant to the level of damage observed after impact and the ballistic performance of the laminate. The tests were performed at quasi-static loading rates using an Instron 4507 testing machine and at high loading rates using a split Hopkinson bar apparatus.

### 4.3 Mode I Interlaminar toughness

Double Cantilever Beam (DCB) tests were used to assess mode I delamination toughness ($G_{IC}$) in terms of the initiation value and the propagation value. DCB testing was completed at low and high rates of opening displacement.

Low displacement rate tests were performed and analysed according to the modified beam theory outlined in ASTM D5528 [5]. High rate evaluation was undertaken according to the description provided by Blackman *et al.* [6], with high speed video images being used to assess dynamic crack opening displacement. The method outlined by Blackman *et al.* [6] was adapted using beam flexure theory to enable analysis using just the crack opening displacement in a similar manner to that defined in ASTM D5528 [5]

### 4.4 Ballistic testing

The ballistic performance of the different sized materials was assessed through V50 trials. V50 is a ballistic test used to determine statistically the threshold velocity at which a projectile would be expected to penetrate a target 50% of the time.

V50 tests were conducted at a ballistics range, using 7.62 mm FSPs (Fragment Simulating Projectiles) for all tests. Velocity measurement at impact was made directly using a laser Doppler system.

## 5. Results and Discussion

### 5.1 Data normalisation

All results in this investigation have been normalised with respect to the performance of the compatible (463) sizing, which is assigned a value of 100. Where testing was carried out at both quasi-static and dynamic rates, data were normalised against the quasi-static performance of the 463 sized material.

### 5.2 Single fibre tension tests

Singe fibre tensile tests were carried out for compatible (463), incompatible (636) and rate dependent smart (ARL) sized fibres and the average measured strengths are shown in Fig 1.

The compatible 463 silane size maintains the highest fibre strength as it simultaneously lubricates the surface to prevent damage and forms a barrier to prevent fibre degradation. The incompatible 636 sized fibres have a measured strength of about 20% less than the compatible system; this is likely to be due to fibre degradation as the 636 size is devoid of silanes and does not provide such effective barrier properties.

The strength of the rate dependent ARL sized fibres was about 55% less than the measured strength of the compatible sized fibres. This decrease is likely caused by a combination of factors including increased surface defects induced by frictional effects of the colloidal silica within the sizing and greater susceptibility to handling damage. This finding is supported by the difficulties associated with pre-pregging of the ARL sized fibres.

### 5.3 Interlaminar shear strength

The average measured interlaminar shear strengths at both static and dynamic loading rates are shown in Fig 2. The incompatible 636 size demonstrated reduced strength indicating a reduction in the structural performance whilst the ARL smart sizing showed increased DNS strength with respect to the 636 size; however the performance of both were lower compared to the compatible sizings. One contributing factor to this could be the high sensitivity of the test method to material defects. The manual processing method required for the ARL specimens resulted in reduced fibre alignment with respect to the commercially prepregged 463, 365 and 636 samples. Fibre misalignment and subsequent resin rich areas are likely to have led to stress concentration and the possibility of premature failure.

A comparison of the static and dynamic double notch shear strength for fibres with various fibre sizings shows increased strength at dynamic rates for all size types. This finding is in agreement with previous dynamic studies where the rate sensitivity of fibre composite systems has been demonstrated [8]. The ARL sized sample displayed the smallest relative increase in the observed strength at dynamic loading rates leading to a change in the ranking between the sizes when transferring from static to dynamic loading. This strain rate sensitivity is a feature of the smart ARL system, where interlaminar strength is compromised for ballistic events whilst structural performance is simultaneously maintained under static and intermediate loading rates.

It should be noted that the semi-compatible 365 size outperformed the compatible size under both static and dynamic loading. However, the actual degree of compatibility for this epoxy system could not be provided by the supplier.

### 5.4 Mode I interlaminar toughness

The quasi-static results indicate that in this loading regime the incompatible sizing system (636) offers significantly improved resistance to crack propagation. This is due to the reduced interfacial strength that encourages extensive fibre bridging of the fractured surfaces behind the advancing crack front. The ARL sample demonstrated the lowest resistance to crack propagation at a static loading rate. This may be due to factors such as fibre bundling promoted by the smart sizing and manufacturing imperfections that serve to compromise the toughness at quasi-static loading rates.

For the dynamic tests, the propagation toughness increased for all size types. The toughness of the compatible and semi-compatible systems each increase by approximately 10%. For the incompatible 636 system, the propagation toughness was increased by 40-50% with respect to quasi-static results.

The ARL specimens showed the largest relative increase in crack propagation resistance when subjected to dynamic loading. Here the propagation $G_{IC}$ increased by about 60% over the values observed under quasi-static loading.

Comparison between the results observed at static and dynamic loading rates supports the findings of the dynamic rate double notch shear tests discussed previously. The use of ARL rate sensitive size has served to increase the crack propagation energy at high loading rates significantly, enhancing dynamic toughness. This increase in toughness is achieved by the promotion of fibre bridging as a result of reduced interfacial strength.

Mode I delamination values for the propagation regime at static and high loading rates are shown in Fig 3 for each of the fibre sizes. The incompatible sized 636 specimen shows a significant propagation value increase from static to dynamic loading rates about 30% higher than the compatible systems. The ARL sized specimens achieved the lowest propagation values at static loading rates but had a higher propagation value than the compatible fibre sizes at dynamic rates.

### 5.5 Ballistic testing

In the ballistic tests, hybrid laminates, containing 25 wt.% incompatible 636 size in combination with 463 or 365 laminates, were found to outperform compatible and semi-compatible laminates of equivalent areal weight. In this instance the incompatible sized plies were placed on the rear face of the laminate, in an attempt to encourage further preferential delamination in this region during ballistic penetration. The visible delamination areas were greater than that achieved with laminates constructed using fibres sized with 463 or 365 in isolation. This suggests that a system of employing a weaker interphase at the rear face can act to encourage preferential delamination.

The measured V50 value indicates an improvement greater than may be expected by random mixing of the incompatible sized plies in the laminate stacking sequence. For example, a 4% improvement in the V50 velocity over 463 laminates was achieved by including 25 wt.% 636 sized plies at the rear face, a factor 4 times greater than would be expected based upon a rule of mixtures. The V50 velocity for panels 463-636 and 365-636 were equivalent, supporting the hypothesis that the action of the rear face plies is critical in determining the V50 performance of the laminate.

V50 ballistic penetration velocities for laminates manufactured using compatible (463), semi-compatible (365), incompatible (636), rate dependent (ARL) and hybrid systems are shown in Fig 4. The presented results for the hybrid systems are for laminates with 463 and 365 sizes with the incorporation of 636 sized plies at the rear face of the panels.

The V50 result is driven by the efficiency of the panel in transferring energy from the projectile due to a combination of effects including elastic strain energy, fibre fracture, fibre pull out and delamination. The compatible 463 size provides the lowest V50 result, followed by the semi-compatible 365 size. These systems have demonstrated the highest interface strength and as a consequence, the observed delamination areas after impact were smaller. Reduced delamination contributes to reduced tendency for the rear plies of the laminate to experience membrane stretching and tensile fibre loading. This feature has previously demonstrated effectiveness in increasing the ballistic perforation energy.

The incompatible size (636) specimens provided the greatest perforation velocity, about 7% higher than an equivalent weight panel with compatible (463) sized fibres. The observed delamination area was significantly greater for this sizing, allowing more effective separation of the rear portion of the panel.

The V50 perforation velocity for the rate dependent ARL sized laminates was greater than the compatible and semi-compatible sized panels and larger delamination areas were observed. Delamination areas were similar to those observed for the 636 sized laminates; however the measured V50 results were not equivalent. It is suggested that the ability of the laminate to transfer energy from the projectile is assisted by the combination of rear face deflection and consequent tensile fibre loading. Consequently, the reduced tensile strength of the ARL sized fibres may be expected to reduce the performance of the plies, compromising to some extent the measured V50 velocity.

## 6. Concluding remarks

Interlaminar shear strength and mode I interlaminar fracture toughness testing has shown that the smart – sized ARL fibres exhibit a significant switch of behaviour at higher strain rates. The low interlaminar shear strength relative to the other sized materials indicates particularly poor structural properties in the ARL material at high rates of testing, whilst the much greater increase in mode I interlaminar fracture toughness for the ARL also indicates a weakening of the fibre matrix interfaces at higher rates of loading. This is supported by observations of the level of bridging present in the ARL specimens which was seen to be greater than for the compatible and semi-compatible sized materials, although still less than that observed for the incompatible 636 sizing.

Ballistic testing suggests that the ARL sizing results in slightly increased V50 performance over compatible sizings although this does not approach the magnitude of the V50 for the 636 material. Observation of the back face delamination of impacted panels suggests that larger delamination areas comparable with the 636 material were present in the ARL panels suggesting that reduced fibre/matrix interfacial strength allowed for greater delamination in the ARL material. The reduced tensile strength of the ARL fibres could potentially have compromised the V50 performance of this material by limiting the energy absorbed through the tensile loading of the fibres.

A hybrid laminate was produced which primarily consisted of the 463 sized material with 25% of the panel made up of 636 located at the rear face. The hybrid panel displayed increased V50 performance above what might be expected through random mixing. The action of the back face is potentially very important to the ballistic performance and the placement of a weaker interface at the rear of a laminate may encourage preferential areas of delamination.

The potential to exploit strategic placement of ballistic optimised fibres could be used to produce structurally improved armour systems with enhanced ballistic protection. The rated dependent behaviour observed for the ARL fibre interfaces also has potential in achieving this goal. The full realisation of this material is contingent on overcoming the issues which lead to the compromised fibre strength.

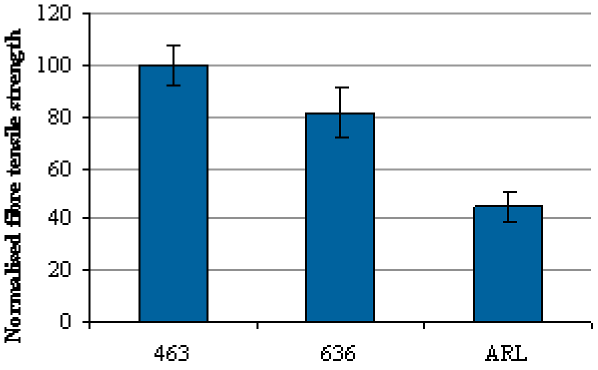

Fig.1. Average fibre tensile strength measured through single fibre testing for compatible (463), incompatible (636) and smart rate dependent (ARL) sized fibres

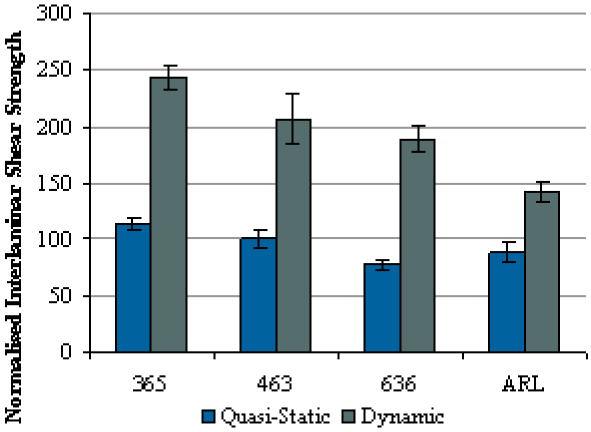

Fig.2. A comparison of the static and dynamic double notch shear strength between fibres with various size treatments.

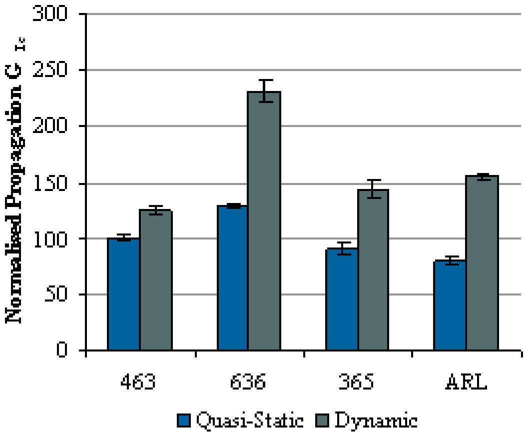

Fig.3. $G_{IC}$ propagation fracture toughness at static and dynamic fracture rates for fibres with various size treatments.

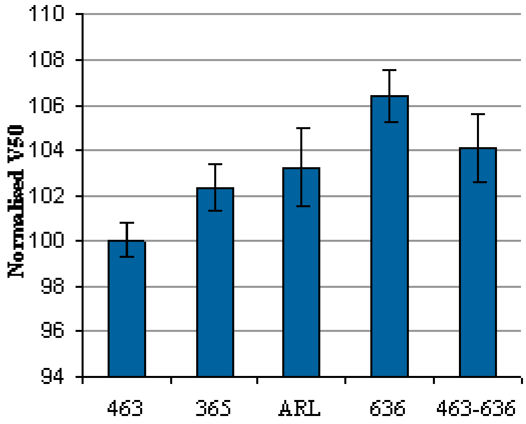

Fig.4. V50 results for panels with various size treatments and hybrid panel 463-636 which has incompatible sized plies on the rear face making up 25% of the total laminate thickness

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## Acknowledgements

The authors gratefully acknowledge funding under the UK MoD MAST programme which has enabled this work. David Fishpool would also like to acknowledge his EngD support from the EPSRC under the MiNMAT Industrial Doctorate Centre at the University of Surrey.