

# AN EXPERIMENTAL COMPARISON OF DIFFERENT CARBON AND GLASS LAMINATES FOR BALLISTIC PROTECTION

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## 1 Introduction

Glass fibre composites find many applications in ballistic resistant panels. S-2 glass and related composites have proven particularly effective in forming the reinforcement in soft armour panels, although the performance has been exceeded in recent years both in absolute terms and on a specific basis, by armour systems based on polyethylene fibres. Glass fibre epoxy armour does possess a higher temperature and fire resistance than polyethylene armour and continues to be an important system. Many armour concepts (e.g. for land vehicles) rely on appliqué armour panels mounted as additional protection systems onto an existing structure, with the appliqué armour not being required to carry any of the structural loads of the vehicle [1].

This is an effective but inefficient approach that results in heavy vehicle, restricting their performance and increasing fuel consumption. There is interest in incorporating the ballistic protection into the main load bearing structure of the vehicle, although this does have some potential problems with repair of damaged vehicles which is very simple when appliqué armour is employed.

While glass fibre composites are effective materials for load bearing structures, they are relatively soft compared to steel, which is widely used as the major structural material for fighting vehicles. There is accordingly an interest in using carbon fibre composites, which can provide a very stiff structure at low weight. It is generally believed however that carbon fibre composites would be inferior to glass fibre composites for ballistic protection, although little experimental data is available.

There is also considerable interest in the development of alternative textile formats for the

reinforcement of ballistic panels. 3D woven architectures are known to possess considerable potential as energy absorbing systems in low speed impacts and it is logical to expect a similar improvement under ballistic conditions relative to 2D fabric based laminates [2,3]. This programme was intended to explore these assumptions by evaluating both glass and carbon fibre laminates experimentally and comparing their ballistic protection for a series of areal weights.

## 2 Textile Architectures 2D and 3D

The glass fibres used in the programme were, for convenience and cost considerations, E-glass. A range of simple 2D plain weave, twill and warp knitted “non crimp” fabrics were used, along with a selection of 3D woven materials with different degrees of interlayer connections (including angle interlock, layer to layer and orthogonal structures). For comparison carbon fibre (T300) fabrics, both 2D plain weave satin weave and NCF, along with an orthogonal 3D were manufactured and tested with similar matrix systems in all cases.

The various textile architectures used in the programme are illustrated in figure 1.

## 3 Experimental details

The laminates were manufactured with a range of areal weights ranging from 3.5 to 7.5 kg/m<sup>2</sup>. Plates were produced using vacuum infusion with a vinyl ester resin. Rectangular samples, 200 mm x 100 mm were cut from the panels and subjected to a ballistic impact with a 0.8 mm, (0.87g) steel sphere fired perpendicular to the clamped plate at speeds up to

500 m/s using a gas gun equipped with a velocity measuring system.

The ballistic limit was measured in each case with this being defined at the impact velocity at which 50% of all projectiles would be stopped by the plate

while 50% would fully penetrate the plate. The limit was established experimentally for each sample configuration by an iterative technique, adjusting the specimen velocities, figure 2. All testing was performed at a nominal room temperature of 20°C

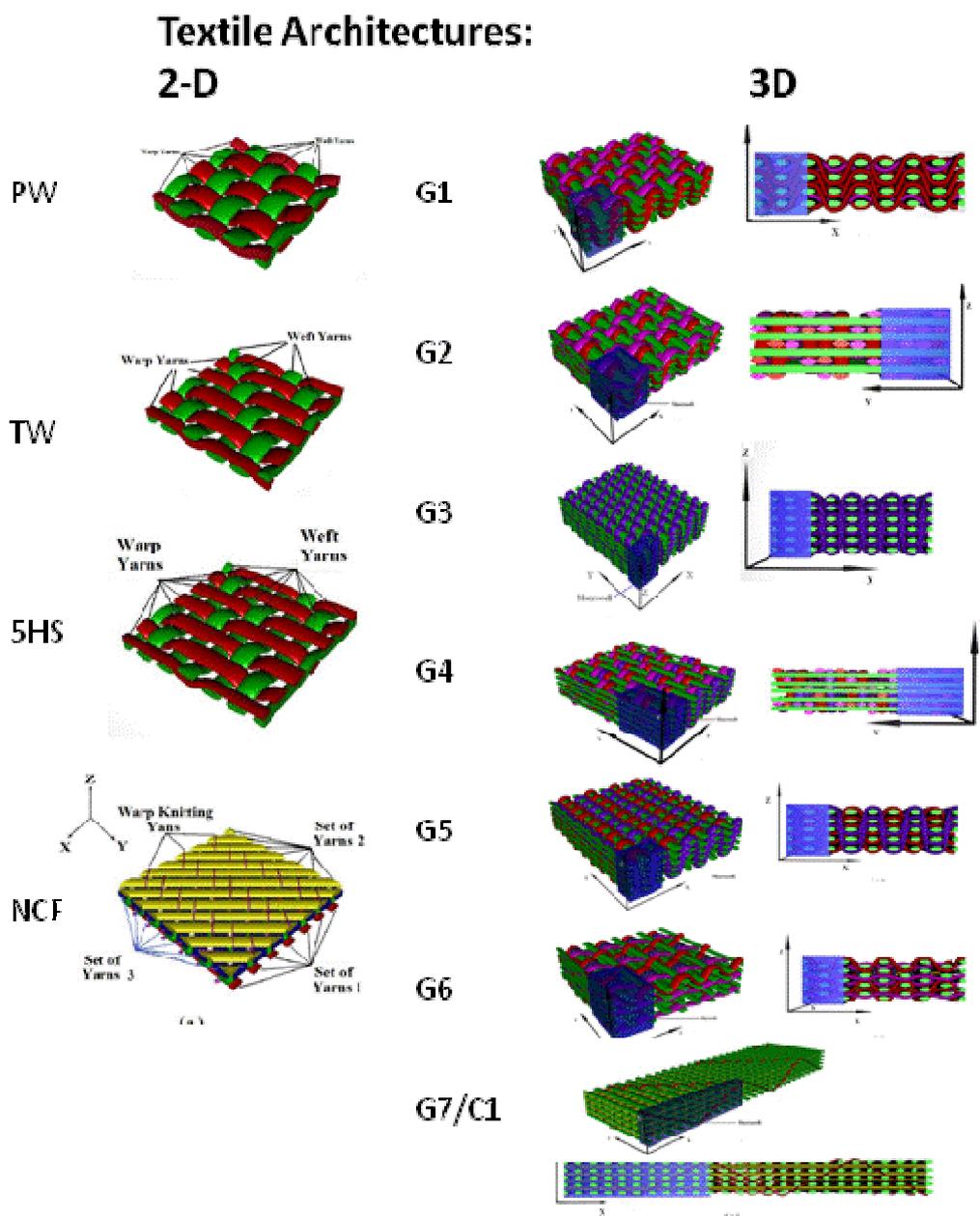


Figure 1. Textile architectures used. PW= plain weave, TW= twill, 5HS= 5 harness satin, NCF= non crimp fabric. G1-G7 are a variety of 3D woven materials produced from glass fibre with G7 being nominally identical to C1, a 3D form used with carbon fibres.

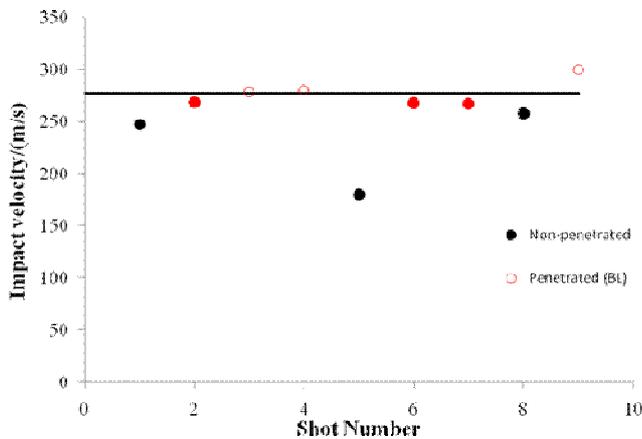


Figure 2. Illustration of the method used to identify the V50 ballistic limit for a batch of specimens.

#### 4. Results

The nature of the damage sustained in laminates as a result of the ballistic impacts was studied by taking optical photographs from polished sections cut through the centre of the impact point.

The projectile travelling at ballistic velocities creates a shear plug near the front face of the composite. The diameter of the shear plug is close to the diameter of the projectile on the first ply and then increases slightly with depth.

Delamination occurs between plies. For relatively thick specimens the diameter of delamination decreased in the first few plies near the top and then increased gradually towards the back face as shown. The delamination is more extensive than the shear plug suggesting that delamination is the major energy absorption mechanism.

For ball projectiles the depth of the shear plug is dependent on the velocity of the projectile. Near the ballistic limit, the shear plug depth was more than  $\frac{3}{4}$  of the specimen thickness.

When specimens were tested just below the ballistic limit, it was observed that the (areal) extent of cracking in the 3D fabric laminates was considerably reduced compared to that in the 2D fabric laminates. The experimental data for ballistic limit was collected individually for each system with ballistic limit plotted versus the areal weight (kg/m<sup>2</sup>) of the panel. The data showed a reproducible polynomial

relationship between the areal weight of the fibre reinforcement and ballistic limit (stopping velocity) as showed in figure 3 for plain woven glass fibre laminates.

What is surprising was that there was no discernable difference between laminates produced from any of the glass fibre architectures studied. The results for the series of non-crimp fabric laminates are shown plotted against the master curve produced for the plain weave samples in figure 4, while the results for the various 3D woven samples are shown plotted against the plain weave results in figure 5. All glass fibre data sets are clearly equivalent, with, if anything a slight reduction in the V50 values for the 3D samples.

The carbon fibre laminates similarly failed to exhibit much of a difference between any of the 2D materials. In this case the data for all architectures, which included NCFs, plain weaves and twill weaves are plotted in figure 6 with a straight line fit.

The plain weave data set for glass fibre laminates is also shown in figure 6. Interestingly, the comparison between glass and carbon fibres shows a very similar level of performance. The glass fibre systems are slightly superior in general although the 3D carbon laminate falls pretty much on the 2D glass fibre curve. It is not certain why the 3D carbon fibre laminate produces slightly superior results to the 2D materials which are in contrast to the glass fibre systems. There may be a small variation in the volume fractions in the respective data sets, although the use of areal weight of reinforcement in the figure should allow for such fluctuations, with the effect of the resin being minimal. It is clear however that the carbon fibre materials have performed reasonably well.

#### 5. Conclusions

The data clearly shows that the ballistic performance of a given fibre system, as measured by the ballistic limit, is independent of fibre architecture and is dependent only on the amount of fibres that need to be broken in order to penetrate the sample. This is similar to the situation in composites subjected to

through penetration impact tests ( velocities 1-5 m/s) where both architecture and matrix effects are minimal, but where the absolute level of protection (measured by impact kinetic energy)is dependent on specimen thickness and volume fraction of fibres.

The work further illustrates that carbon fibre laminates have good potential as structural materials for use in structures with a built in-ballistic capability. The performance is more or less equivalent to E-glass and as such is inferior to S-2 glass and similar fibres. However the stiffness of the laminate is such that it may be possible to create a structure with adequate ballistic protection for a given threat level whilst maintaining a weight advantage relative to steel.

### 6. Acknowledgments

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Reinforcements supplied the 3D carbon fibre and the glass fibre NCFs

### References

- [1] V. S.Galvez, L. S. Paradelo, Analysis of failure of add-on armour for vehicle protection against ballistic impact, Engineering Failure Analysis, Volume 16, Issue 6, Papers presented at the Third International Conference on Engineering Failure Analysis (Sitges, Spain, 13-16 July 2008) Part II, September 2009, Pages 1837-1845, ISSN 1350-6307
- [2] Y.A..Bahei-El-Din, M.A..Zikry, Impact-induced deformation fields in 2D and 3D woven composites, Composites Science and Technology, Volume 63, Issue 7, May 2003, Pages 923-942
- [3] N.K. Naik, P. Shirao, B.C.K. Reddy, Ballistic impact behaviour of woven fabric composites: Formulation, International Journal of Impact Engineering, Volume 32, Issue 9, September 2006, Pages1521-1552

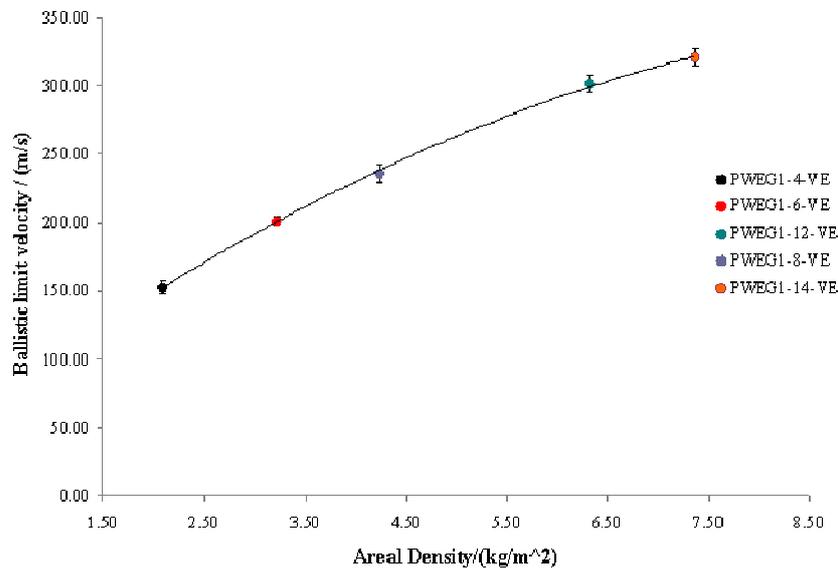


Figure 3. Ballistic limit for plain weave E-glass fibre samples as a function of preform areal weight

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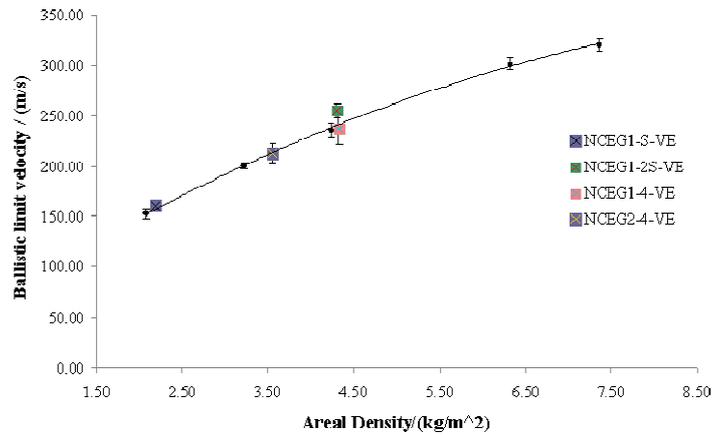


Figure 4. Ballistic limit values for non crimp fabric E-glass fibre samples as a function of preform areal weight plotted on the master curve generated from the plain weave samples shown in figure 3

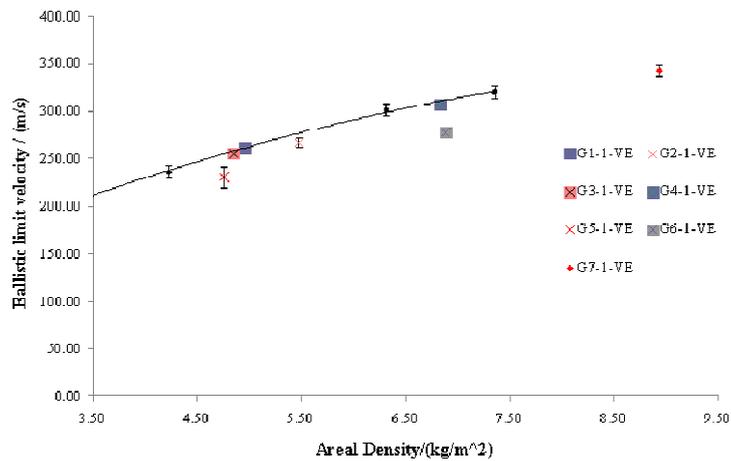


Figure 5. Ballistic limit values for 3D woven E-glass fibre samples as a function of preform areal weight plotted on the master curve generated from the plain weave samples shown in figure 3

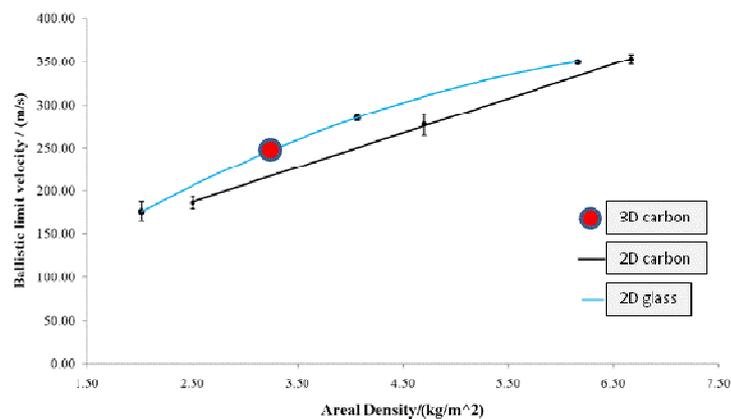


Figure 6. Ballistic limit values for 2D and 3D carbon fibre samples as a function of preform areal weight plotted alongside the master curve generated from the glass fibre plain weave samples shown in figure 3