J Mater Sci (2008) 43:6619–6629
DOI 10.1007/s10853-008-2787-7

STRETCHING THE ENDURANCE BOUNDARY OF COMPOSITE MATERIALS: PUSHING THE PERFORMANCE LIMIT OF COMPOSITE STRUCTURES

The response of carbon fibre composites to blast loading via the Europa CAFV programme

Andy Wright · Mark French

Received: 26 April 2008 / Accepted: 6 June 2008 / Published online: 16 August 2008

Abstract Modern military vehicles must balance the need for occupant protection against the competing requirements for high mobility and payload capacity. As such, there is continuing interest in the development of lightweight vehicle structures that reduce the overall mass of the hull and armour system, leading to a lighter vehicle. One way to achieve this is through the use of materials that can perform both structural and protective roles, reducing the mass of appliqué armour required to achieve a given level of protection. The aim of the 3-year EUROPA Carbon Fibre for Armoured Fighting Vehicles (CAFV) programme was to investigate the use of carbon fibre composites for use in military vehicle structures. Six nations took part in the programme, each assessing the benefits of carbon fibre composites in terms of their application to at least part of an armoured fighting vehicle (AFV) hull. For the UK, a lower hull section was selected as the focus for the research programme and, as part of the programme, assessed against mine blast threats.

Introduction

Modern military vehicles must balance the need for greater mobility against increasing payload requirements, and these competing goals are continuing to drive the development of armoured fighting vehicles (AFVs). With the associated demands for lighter protection systems and improved occupant protection, there has been an increasing move towards materials which are capable of fulfilling both structural and protective roles.

Fibre reinforced composites offer an attractive combination of structural performance and low density. In particular, carbon fibre reinforced plastics (CFRP) display excellent specific structural properties and, as a result, CFRP solutions have been the subject of increasing interest within the research community.

The UK research programme

As part of the multi-national EUROPA research initiative, the UK research consortium (QinetiQ, BAE Systems and VT Halmatic) investigated the use of CFRP for the construction of a hull floor for an AFV. In addition to fulfilling the necessary structural requirements, the floor must also provide an optimised level of protection against kinetic energy and blast threats. While carbon fibre offers many advantages as a structural material, its performance against blast was unknown. It is highly likely, however, that protection against common anti-tank mine threats (such as those defined by NATO STANAG 4569 [1]) could be achieved using CFRP alone. For this reason, the focus of the UK research programme was to identify a carbon fibre-based composite material that offers an optimum combination of structural performance, blast protection and low cost through a integrated combination of numerical modelling and experimental assessment.

Mine blast loading of vehicle structures

In assessing the performance of materials against blast loading, it is critical that the test loading applied to the material is representative of that experienced during a mine

A. Wright (✉) · M. French
QinetiQ, Room 2012, Building A5, Cody Technology Park,
Farnborough, Hampshire GU14 6EN, UK
e-mail: AJWright1@QinetiQ.com

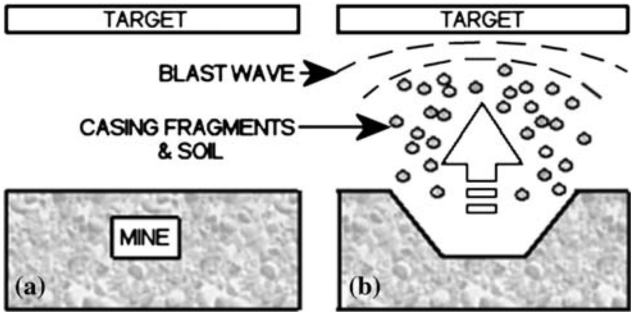


Fig. 1 Schematic view of mine blast event (**a**) prior to detonation and (**b**) post-detonation

blast event. Mine blast loading is, in itself, a complex problem, and while a number of "ready reckoner" methods exist (e.g. ConWep [2]) to estimate the loading associated with a given explosive content, it can be difficult to accurately simulate loading histories for this type of threat (Fig. 1).

Much of this complexity relates to the position of the mine, which is generally buried beneath a layer of soil, or at least partially buried such that the top surface of the mine is flush with the ground. Sub-soil mine blast loading can be separated into two principle components: blast loading due to the explosive within the device, and particulate loading caused by the impact of soil and casing fragments, to which energy has been transferred. The nature of the soil, and in particular moisture content, can significantly influence the contribution from particulate loading as part of the overall load.

To simplify the problem, it is possible to consider the blast load in isolation, since this is usually the dominant factor. To eliminate the variation in loading conditions due to the influence of soil properties, a procedure similar to that described in Allied Engineering Publication 55 Volume 2 [3] can be employed, in which a bare explosive charge is positioned within a metal cup or pot. On detonation, explosive materials decompose and expand extremely rapidly, compressing the air adjacent to the surface, which in turn leads to the formation of a high-pressure, high-velocity shock wave. This shock wave then travels rapidly outwards from the surface of the charge, until it reaches the surface of a target structure. The incident shock wave is characterised by an instantaneous increase from atmospheric pressure to a peak value, followed by a steady decay, as illustrated in Fig. 2. Over time, the pressure reduces below atmospheric pressure, resulting in a negative phase region. As time passes, the pressure will oscillate one or more times between positive and negative phases.

The effect of blast loading on a target structure can be characterised in terms of the peak overpressure, impulse and blast focussing, as follows:

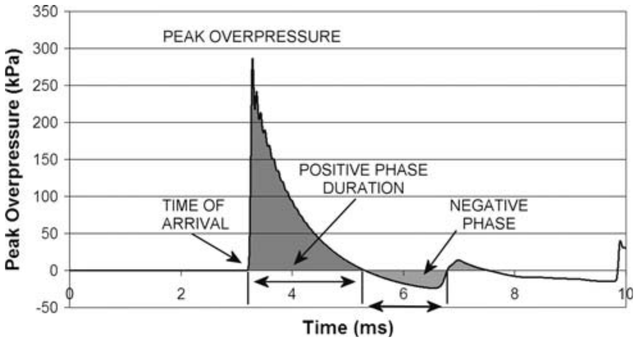


Fig. 2 Typical shock wave associated with an explosive event, illustrating characteristic blast parameters

Peak overpressure

Peak overpressure provides a measure of the maximum instantaneous load experienced by the target structure. During blast loading, the impact of the high-pressure shock wave on the outer surface of the target generates a compressive stress wave within the material. If this instantaneous pressure exceeds the compressive strength of the target material, some degree of crushing failure may occur. The stress wave then propagates through the material until it reaches the rear face of the target, where it is reflected as a tensile wave. As before, if the amplitude of this wave exceeds the tensile strength of the material, further damage may occur. In composite materials, the compressive stress wave can cause crushing failure of the polymeric matrix, while the reflected tensile wave is responsible for localised through-thickness delamination.

Impulse

Impulse provides a measure of the energy transferred to the target structure, and may be determined from the area underneath the pressure–time curve for the blast loading event. To a large extent, impulse controls the level of target deflection, which can result in both tensile and compressive fibre failure in composite materials. The rate of energy transfer, as defined by the slope of the impulse–time curve, is also important as this controls the strain rate experienced by the target material.

Blast focussing

Blast focussing simply describes the localisation of loading over a relatively small area of the target surface. In mine blast events, this localisation occurs as a result of both explosive charge geometry and confinement, but it can also be influenced by stand off distance (between the explosive and target) since the distance (and angle of incidence) between the detonation point and the target surface will vary with position across that surface. Where a target is subjected to a highly localised blast load, the substantial variation in peak pressure across the target surface can result in shear damage and through-thickness material failure, referred to as “shock holing”. For more evenly distributed loading, through-thickness material failure is less likely to occur, although there will be a greater likelihood of failure around joints and corners.

Small-scale tests

Blast testing of large vehicle structures can be extremely costly and time consuming, particularly given the large number of variables possible with composite materials and the need to ensure repeatability of results. For this reason, it is highly desirable for the performance of candidate materials to be assessed using small-scale tests that attempt to replicate, as closely as possible, the loading conditions experienced during a mine blast event.

At the beginning of the programme, five candidate materials were selected for initial assessment using small-scale blast trials (Table 1). In addition to providing an early indication of the most promising solutions, the small-scale trials provided valuable experimental data for model validation. The relative performance of the candidate materials was assessed in terms of the threshold charge weight for a fixed stand off distance, defined as the charge weight of explosive required to cause maximum damage without through-thickness rupture.

Small-scale testing was undertaken using 800 mm × 800 mm targets. The relative level of resistance to blast loading was assessed on a weight for weight basis, against a benchmark 28-mm-thick carbon/epoxy laminate with an areal density of approximately 42 kg/m^2. In order to replicate the highly focussed loading associated with a mine blast event and minimise the influence of boundary effects, a stand off distance of 150 mm was employed. The level of blast loading (in terms of peak overpressure and impulse) was controlled by varying the mass of the spherical charge. In addition to comparing the performance of a number of composite laminates, performance was also assessed against that of a conventional rolled homogenous armour (RHA) steel of equivalent weight per unit area. The small-scale trial arena used is illustrated in Fig. 3, while the results of the small-scale blast trials are illustrated in Table 2.

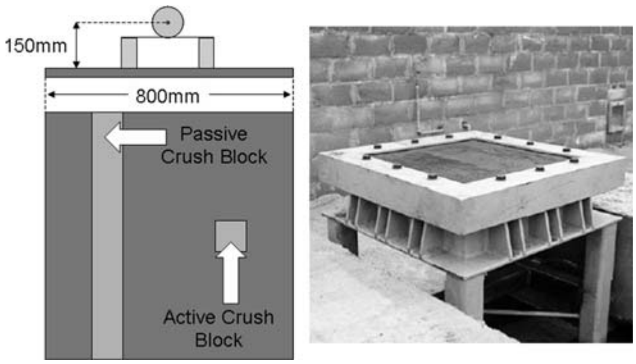


Fig. 3 Small-scale trial arena used to assess relative blast resistance of candidate material samples

Model development

Following the initial small-scale blast trials, the ability of commercially available modelling tools to predict the resistance of composite targets to blast loading was assessed. The model assessment programme focussed on the use of dynamic finite element codes AUTODYN and LS-DYNA to predict the blast response of composite structures in terms of rupture, dynamic deflection and residual damage. These factors can be used to estimate the

Table 1 Details of candidate materials assessed as part of the UK research programme

Material	Fibre	Matrix	Comment
Standard carbon	Tenax STS 24k non-crimp fabric (NCF), quasi isotropic	Standard epoxy	28-mm-thick baseline solution, with areal density of 42 kg/m^2
Toughened carbon	Tenax STS 24k non-crimp fabric (NCF), quasi isotropic	Toughened epoxy	Toughened matrix materials provide improved impact performance. Unknown influence on response to ballistic and blast threats
Tufted carbon	Tufted 3D carbon fibre architecture	Standard epoxy	Through-thickness reinforcement is thought to result in reduced delamination
E Glass/carbon hybrid	E Glass/STS 24k (50/50 by weight) with alternating plies in balanced lay-up	Standard epoxy	Lower cost material than all-carbon solution
S2 Glass/carbon hybrid	S2 Glass/STS 24k (50/50 by weight) with alternating plies in balanced lay-up	Standard epoxy	Intermediate cost between E glass hybrid and all-carbon solution. S2 glass offers improved ballistic performance compared to conventional E glass

Table 2 Summary of small-scale-blast trial results for various targets of equivalent areal density (42 kg/m^2), “P” indicates no through-thickness rupture (pass), while “F” indicates a fully ruptured target (fail)

Material	Charge mass										
	600	675	750	788	825	863	900	975	1,200	1,275	1,500
100% CFRP	P		PP		F		F				
Carbon/E glass hybrid		P	FF			F					
Carbon/S2 glass hybrid			P		PP	F	PFF				
100% S2 GFRP			P	PP	F			F			
100% E GFRP			P	P	F						
RHA									P	F	F

likelihood of occupant injury resulting from blast overpressure, fragment impact and spinal loading.

In order to achieve a balance between accuracy and efficiency, the blast load was initially represented using load curves. Load curves were derived for a range of C4 explosive charge weights in air using 2D axisymmetric Eulerian simulations in AUTODYN, with the target surface represented by a rigid boundary along one edge of the mesh, as illustrated in Fig. 4. Gauge points were positioned at regular intervals along the target surface to record the pressure–time history for each charge size, which could then be directly applied to a target model in either AUTODYN or LS-DYNA, allowing direct comparison between the two codes.

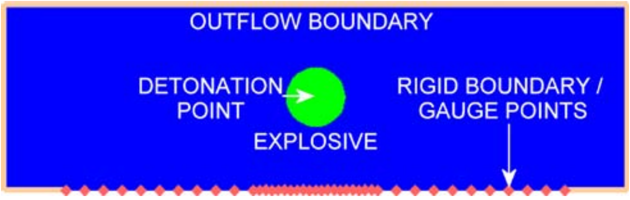


Fig. 4 Overview of load curve generation model for 750 g spherical C4 charge, positioned 150 mm from the target surface

Due to the extreme conditions experienced at the target surface, direct validation of the pressure time histories generated by the model was not possible and the blast model was instead validated using a combination of direct and indirect techniques. Firstly, a model of the small-scale test site was constructed, including the target, test rig and a neighbouring wall with an attached surface pressure gauge, allowing direct validation of pressure-time histories against experimental data from a far field pressure gauge in terms of time of arrival, peak pressure and impulse (Fig. 5). Secondly, the results of additional tests, undertaken using 5.5 mm rolled homogenous armour (RHA) targets, were used to provide indirect validation of the nearfield blast load in terms of both initial dynamic and final deformations. A well-established Johnson Cook material model [4] was used to represent the RHA target, in combination with a shock/Gruneisen equation of state. The results of the

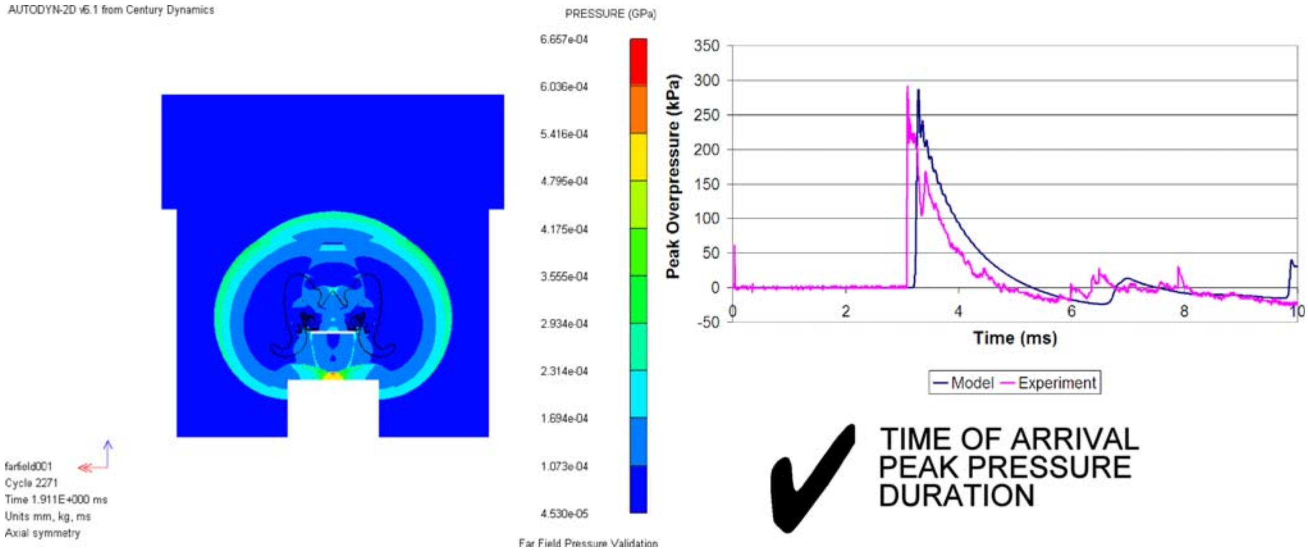


Fig. 5 Comparison between 2D axisymmetric modelling results and experimental pressure–time data for a 750 g spherical C4 charge, 150 mm from the target surface

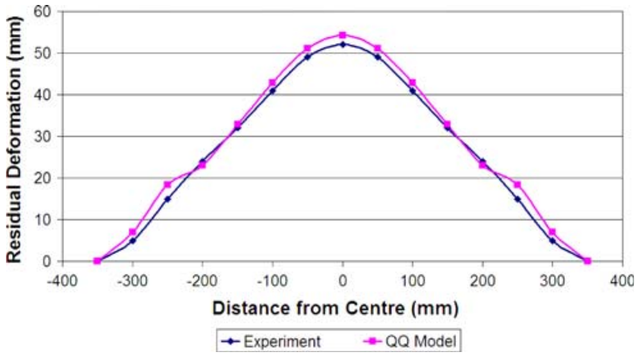


Fig. 6 Comparison of modelling results for residual deflection with experimental results for a 5 mm RHA panel loaded by 750 g spherical C4 charge at 150 mm stand off

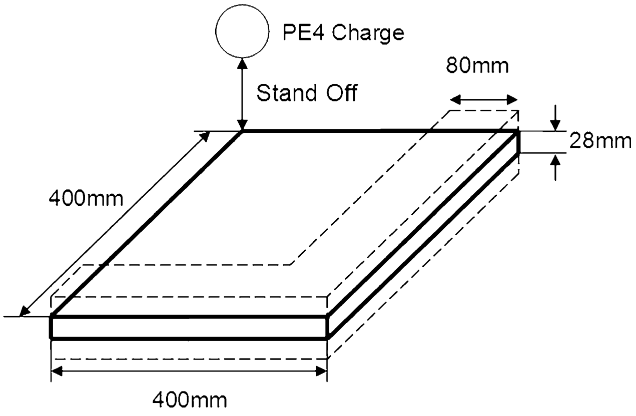


Fig. 7 Quarter symmetry model used to predict blast response of carbon fibre composite laminates

RHA target simulations are illustrated in Fig. 6 and demonstrate the level of agreement achieved.

For the composite targets, a quarter symmetry model was constructed, as illustrated in Fig. 7. Load curves were applied to the target surface, corresponding to the gauge point locations in the Eulerian blast load simulations. In LS-DYNA, both shell and solid element models were employed to assess the influence of through-thickness effects on blast loading response. For both shell and solid element models, the composite target was represented using the MAT_COMPOSITE_FAILURE_*OPTION*_MODEL (MAT#59), where *OPTION* is replaced by SHELL or SOLID, depending on the element type used. In AUTODYN, the orthotropic yield/softening model was used to represent the composite target. In both codes, material properties were initially based on mechanical test data, obtained as part of the EUROPA research programme, for quasi-isotropic carbon/epoxy laminates (Table 3).

The results of the LS-DYNA blast response models are summarised in Figs. 8–10. In LS-DYNA, the predicted damage mechanisms provide good qualitative agreement with the development of damage in response to blast loading (Fig. 9). In particular, the development of delamination along the neutral axis of the panel (under bending) agrees well with the damage observed in sectioned samples. The dynamic deflection response predicted by the model also shows good agreement with experimental results, up to a time of approximately 0.8 ms (Fig. 10). The quantitative resistance of the composite to blast loading, however, is significantly underestimated, with a threshold charge weight of approximately 600 g. At 750 g, experimental targets displayed extensive damage without through-thickness rupture, while the model predicted full through-thickness failure. This highlights the problems associated with a simple, stress-based failure criteria and the absence of an accurate model for the post-failure mechanisms, which are responsible for significant levels of energy absorption in composite materials.

As discussed previously, simulations were also undertaken in AUTODYN, which features a recently implemented orthotropic yield/softening model [5] to describe the response of composite structures to blast loading and high-velocity impact. The input data required for this model is

Table 3 Material property data used to represent carbon/epoxy laminates

Material model	*MAT_COMPOSITE_FAILURE_*OPTION*_MODEL		
Property	Value	Property	Value (MPa)
Density	1,560 kg/m^2	Shear strength (ca)	60
Young's modulus (x direction)	45 GPa	Shear strength (cb)	60
Young's modulus (y direction)	45 GPa	Compressive strength (x direction)	480
Young's modulus (z direction)	8.5 GPa	Compressive strength (y direction)	480
Poisson's ratio (ba)	0.698	Compressive strength (z direction)	600
Poisson's ratio (ca)	0.08	Tensile strength (x direction)	650
Poisson's ratio (cb)	0.08	Tensile strength (y direction)	650
Shear modulus	17 GPa	Tensile strength (z direction)	40
Shear strength (ba)	320 MPa		

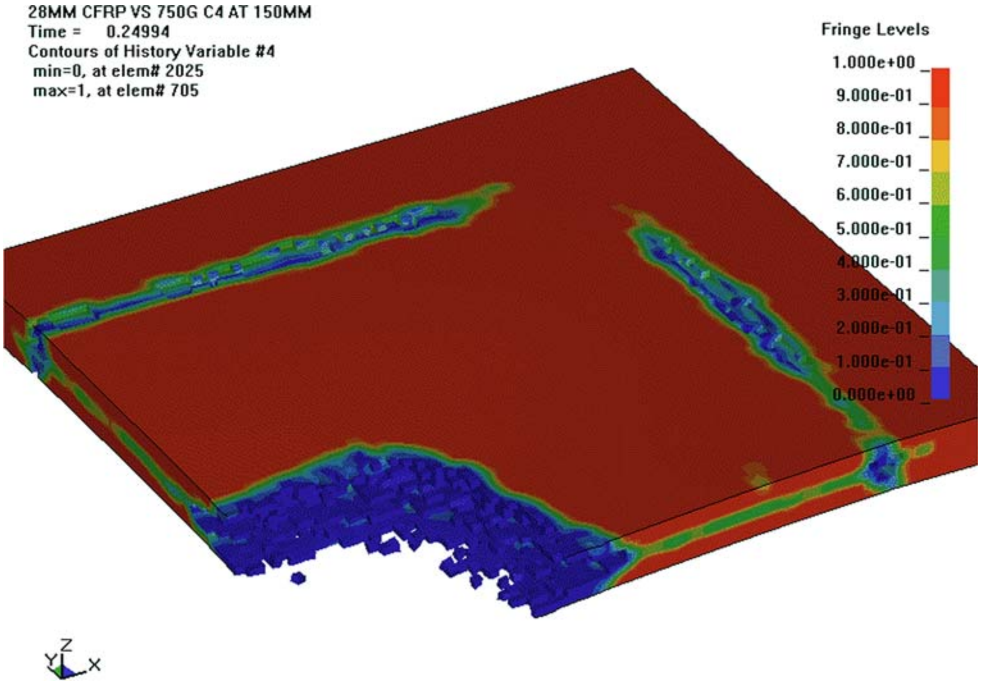


Fig. 8 Predicted response of carbon/epoxy laminate to blast loading by 750 g C4 charge at 150 mm stand off. Contours indicate the extent of delamination damage within the target, with complete failure predicted in the centre of the target

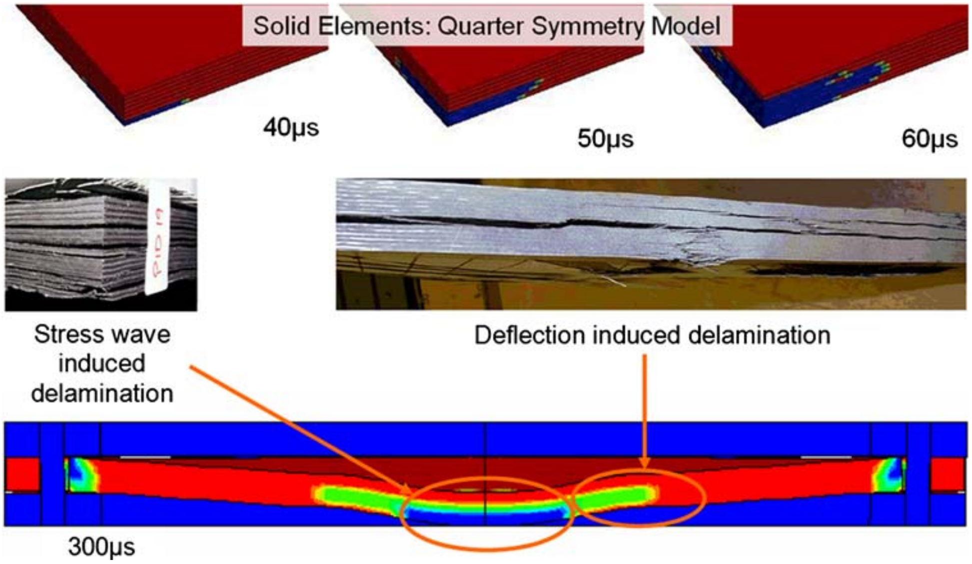


Fig. 9 Delamination damage predicted by LS-DYNA carbon/epoxy composite target model in response to blast loading by a 600 g spherical C4 charge, at a stand off of 150 mm from the target surface

perhaps best described as extensive, and the first difficulty in its application is the lack of readily available mechanical property data for a range of composite materials. While the AUTODYN user documentation [6] provides detailed information on the methods used to determine the various parameters, a large number of tests are required, resulting in a high development cost for a working model. In this initial assessment, therefore, a built-in kevlar/epoxy laminate model [7] was used as a basis for the CFRP, with known material data for carbon/epoxy laminates (Table 3) substituted wherever possible. To assess the behaviour of this model, a series of simulations were completed for 600, 750 and 825 g of C4 explosive at a stand off of 150 mm. Due to the quasi-isotropic nature of the candidate materials, a 2D axisymmetric model was used, with rigid boundary conditions applied at the outer edge of the target.

The results of the simulations are illustrated in Figs. 11–13 and show a steadily increasing level of through-thickness (DAM11) and in-plane damage (DAM22/TT) through the thickness of the target panel in response to an increasing level of blast loading. Extensive delamination begins at the rear of the target, as expected due to reflection of the initial compressive stress wave at the rear surface, and extends through the entire thickness of the panel for a

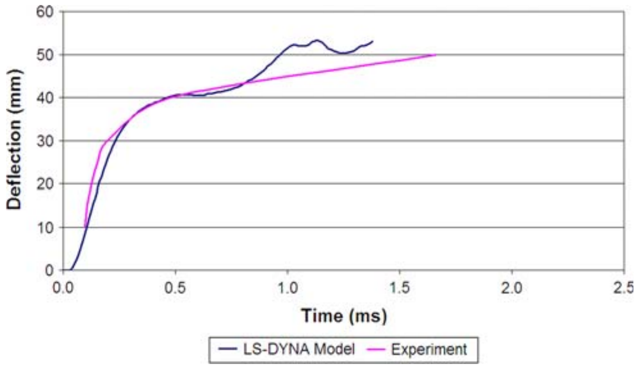


Fig. 10 Comparison of timed deflection response predicted by numerical model in LS-DYNA with experimental results for a 28-mm-thick carbon/epoxy laminate subjected to blast loading by a 600 g spherical C4 charge at 150 mm stand off

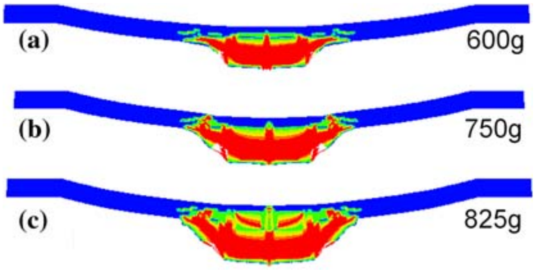


Fig. 11 Predicted levels of through-thickness damage for carbon/epoxy laminates

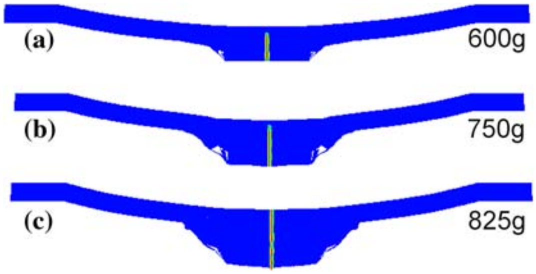


Fig. 12 Predicted levels of in-plane damage for carbon/epoxy laminates

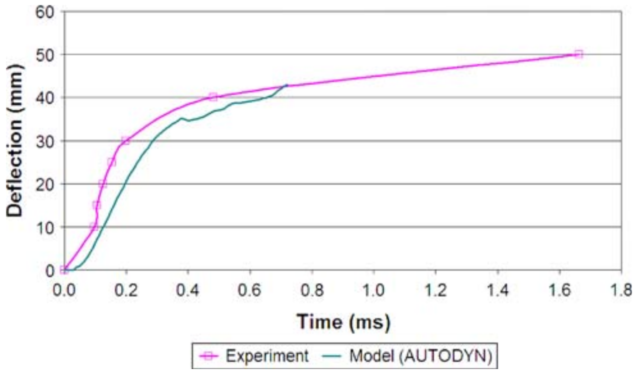


Fig. 13 Comparison of results of 2D axisymmetric simulation in AUTODYN for dynamic deflection with experimental data for a 28-mm-thick carbon/epoxy laminate subjected to blast loading by 600 g spherical C4 charge at 150 mm stand off

Table 4 Comparison of normalised quasi-static property data for monolithic and hybrid laminates

Laminate	Tensile strength (MPa)	Tensile modulus (GPa)	Tensile strain to failure (%)
100% Carbon	554	53	1.0
100% E Glass	409	25	2.6
100% S2 Glass	461	25	2.6
50% Carbon + 50% E Glass	402	29	1.6
50% Carbon + 50% S2 Glass	331	32	1.3

charge weight of 750 g (Fig. 11b). Examination of DAM22/TT variables provides an indication of in-plane damage, although it is difficult to identify the exact mode of failure (fibre/matrix) since the material is effectively treated as homogeneous. From Fig. 12, however, it is clear that in-plane failure also increases with charge size and, at a charge weight of 825 g, extends through the full thickness of the target. The predicted threshold charge weight using this approach is therefore 750 g. This highlights the differences between the material model used in LS-DYNA, which displays a brittle failure response, and that used in AUTODYN, which includes the material's progressive softening behaviour after the initiation of failure. Based on the results of the preliminary modelling study, the inclusion of post-failure response is critical to understanding the response of composites to blast loading.

Hybrid material modelling

During the small-scale experimental trials, carbon/S2 glass hybrid laminates were identified as the most promising solution in terms of resistance to blast loading without rupture. In order to predict the response of hybrid structures to blast loading, therefore mechanical testing was undertaken to provide model input data. The results of tensile testing are summarised in Table 4, and indicate a reduction in strength and stiffness due to hybridisation without a significant increase in strain to failure. Consequently, the modelling of hybrids was limited by the mechanical property data obtained. Investigation of the tested samples indicated that failure in the hybrid was premature due to delamination in the specimens. Further work into hybrid test methods is therefore required.

The results of tensile testing suggest a reduced level of energy absorption before the initiation of failure in hybrid laminates, particularly in the case of the carbon/S2 hybrid. When used as input data for the finite element simulations the available mechanical properties for the hybrid laminates result in rupture at lower charge weights (for a brittle failure models) or an earlier initiation of failure (for models which incorporate softening effects). This runs contrary to the results of the small-scale blast tests, which demonstrated that the threshold charge weight for the carbon/S2 hybrid was at least 10% greater than that of the other candidate materials.

Large-scale demonstrations

The purpose of the large-scale demonstration tests, undertaken at TNO's Ypenburg facility in May 2007, was to demonstrate the vehicle-scale performance of carbon fibre-based composites against mine blast loading. In this case, the mine was represented using cylindrical charges, with a constant aspect ratio of 1/3, positioned within a steel pot at a surface-to-surface stand off of 520 mm, as illustrated in Fig. 14. As only a limited number of firings were available, numerical modelling was used to provide an estimate of the threshold charge weight required for rupture.

Carbon/S2 hybrid laminates were identified during the small-scale trials as offering the greatest resistance to blast loading out of the candidate materials under investigation and, on this basis, were selected for use in the large scale demonstration tests. Due to the complexities of modelling hybrid laminates, however, it was necessary to identify an alternative method that could be used to predict the threshold charge weight for rupture when using a pot charge. As discussed previously, good agreement was noted between the results of AUTODYN simulations and experimental results for 100% carbon/epoxy laminates, while the threshold charge weight for carbon/S2 glass hybrid laminates was found to be at least 10% higher than for a 100% carbon laminate of equivalent weight. The large-scale modelling study, therefore, focussed on predicting the response of a 100% carbon/epoxy laminate, with an empirical charge weight uplift of 10% to account for the improved performance of the carbon/S2 hybrid.

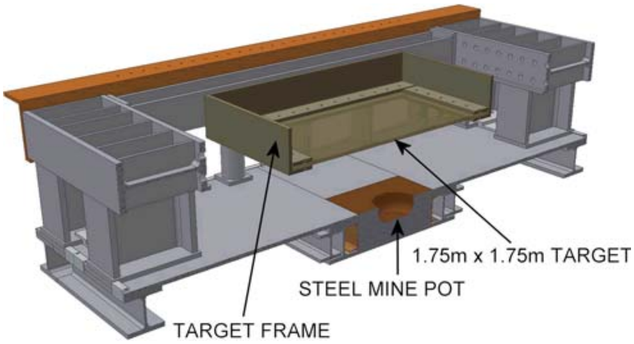


Fig. 14 Cross-sectional overview of large-scale test rig used for application case demonstration trials (image courtesy of TNO)

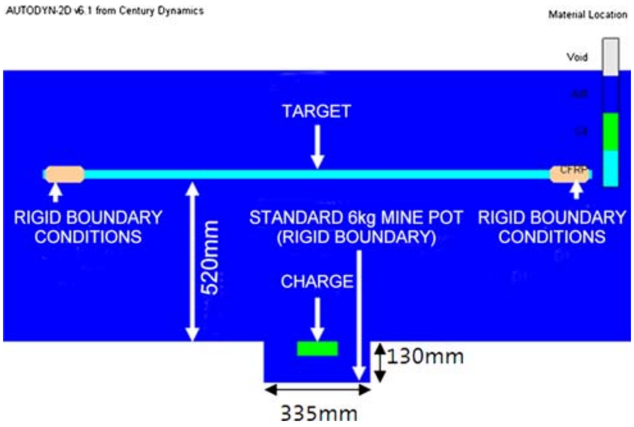


Fig. 15 Overview of 2D axisymmetric model employed during large-scale mine blast modelling study

An overview of the 2D axisymmetric AUTODYN model used for the large scale simulations is shown in Fig. 15. As indicated, the frame was initially represented using a fixed-velocity boundary condition, corresponding to the position of the bolts during the physical test. The results of the modelling runs predicted failure at a charge weight of between 800 and 1,000 g, as illustrated in Figs. 16 and 17. On the basis of the numerical modelling results, after applying the empirical 10% uplift, blast testing of the large-scale targets was undertaken for charge weights of 900 and 1,100 g.

The post-test condition of the target panels is illustrated in Fig. 18. No rupture of the composite laminates was observed, indicating that the finite element models had underpredicted the performance of the laminates. Comparison of the predicted and measured deflection and velocity profiles (Fig. 19) revealed that, while the initial dynamic response showed good agreement, the peak dynamic deflection of the physical targets was greater than that predicted by the model.

Further examination of the target and test frame after the trial indicated that the inner steel frame, used to position the target above the surrogate mine charge, had undergone appreciable plastic deformation under blast loading. In light of this, the blast simulation for a 1,100 g charge was re-run with the fixed-velocity boundary replaced by a flexible steel frame, as illustrated in Fig. 20. The dynamic deflection results of the revised model are illustrated Fig. 21, and show improved agreement with experimental results after 1 ms, with no prediction of target rupture.

Conclusions

The project has demonstrated that CFRP materials can be modelled using commercial dynamic finite element analysis packages (LS-DYNA/AUTODYN) to predict blast

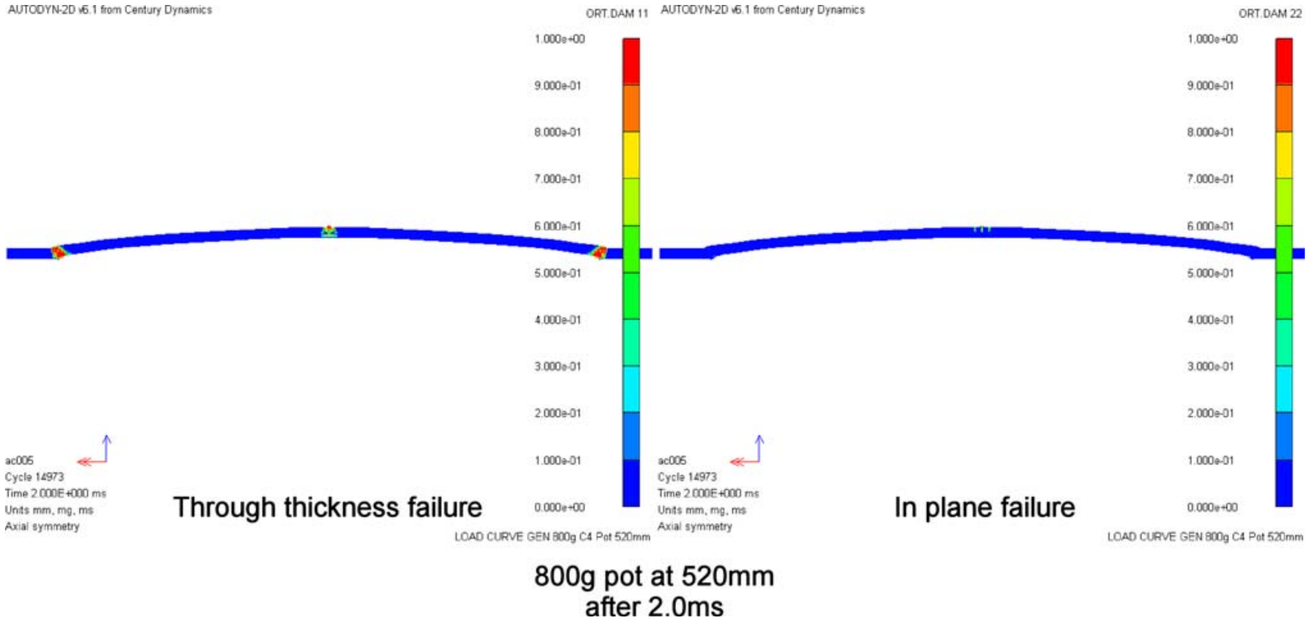


Fig. 16 Predicted response of 28-mm carbon/epoxy laminate to blast loading by 800 g mine pot charge at (surface-to-surface) stand off distance of 520 mm showing incomplete failure

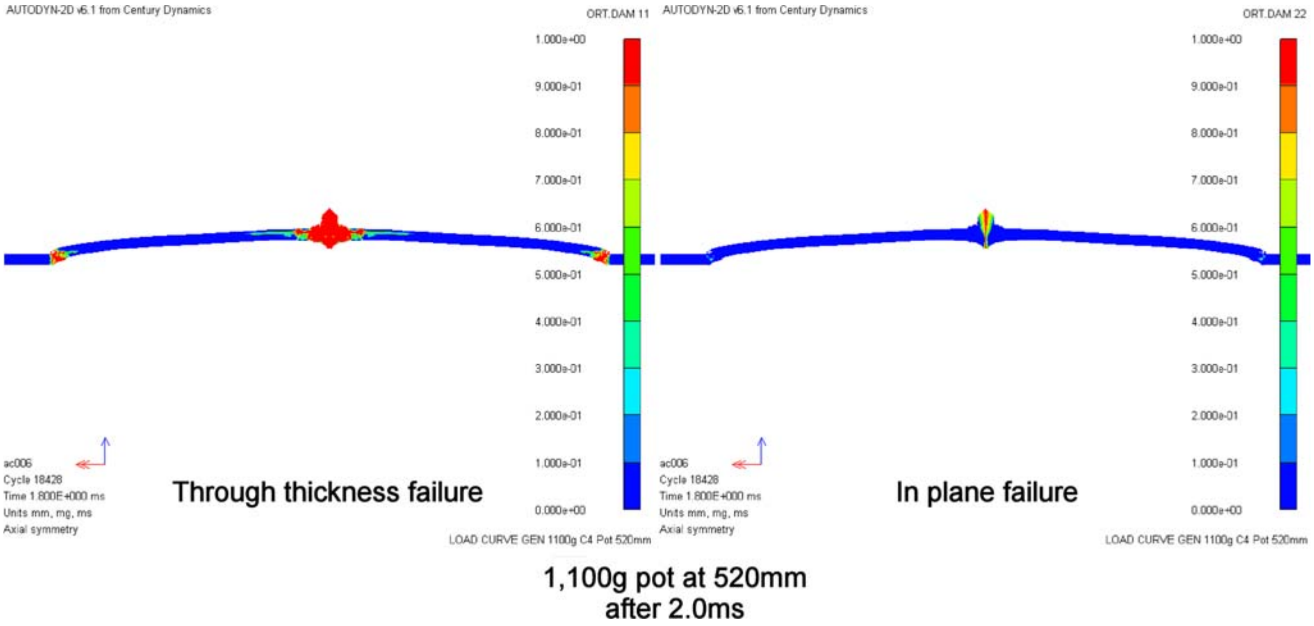
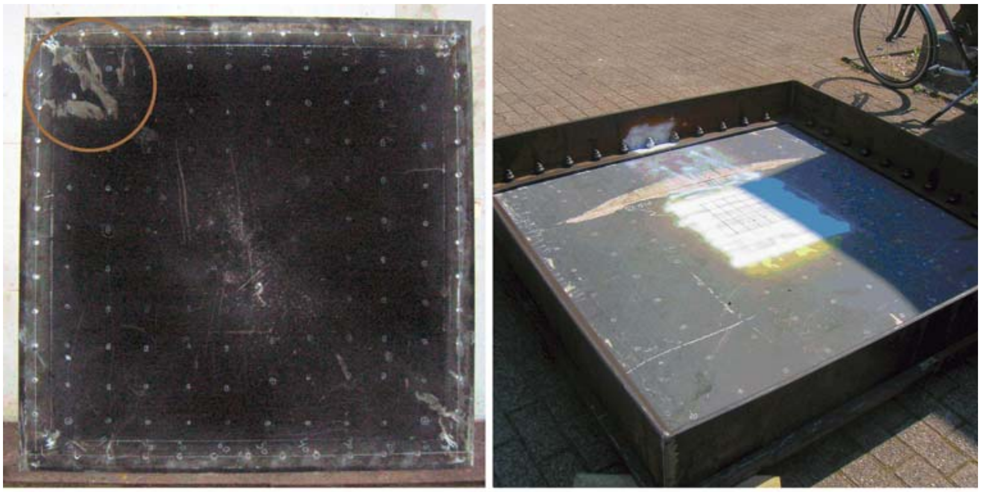


Fig. 17 Predicted response of 28-mm carbon/epoxy laminate to blast loading by 1,000 g mine pot charge at (surface-to-surface) stand off distance of 520 mm showing complete through-thickness failure

performance. For composite laminates, the strength and stiffness properties that control the response of the structure until the initiation of failure are relatively well understood, and can be modelled with a reasonable degree of accuracy. Where composite materials present a severe challenge, however, is in modelling failure response, especially the energy absorbed by active failure mechanisms.

In particular, the response mechanisms of hybrid laminates are not well understood. The results of finite element models are closely tied to the availability of property data that accurately describes the response of the material to the applied load, including any rate effects. For hybrid laminates, the improvement in blast performance cannot currently be directly linked to static mechanical properties, and this presents a significant challenge in terms of

Fig. 18 Post-test condition of large-scale test samples



Front surface of 28mm S2 / Carbon Hybrid laminate, loaded by 900g C4 pot charge at surface to surface stand off of 520mm

Rear surface of 28mm S2 / Carbon Hybrid laminate, loaded by 1,100g C4 pot charge at surface to surface stand off of 520mm

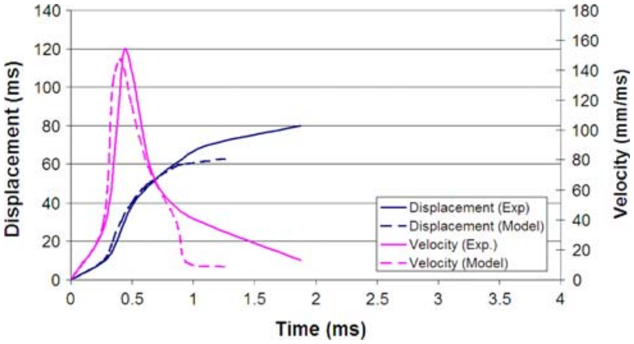


Fig. 19 Comparison of predicted dynamic deflection response with experimental results for 28-mm carbon/S2 hybrid laminate subjected to blast loading by 900 g C4 pot charge at surface-to-surface stand off of 520 mm

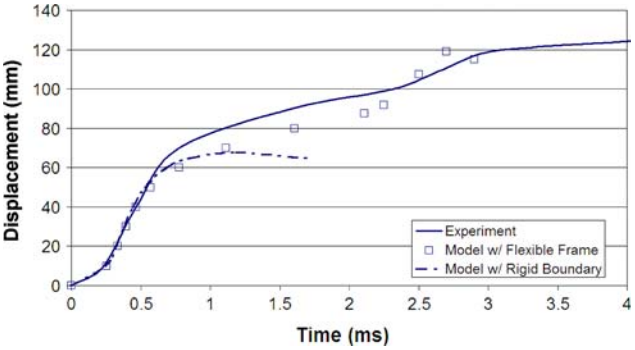


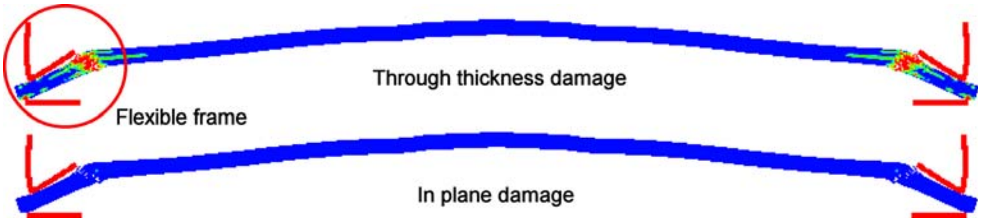
Fig. 21 Comparison of dynamic deflection predictions for both rigid and flexible boundaries with experimental results

material characterisation when compared with metallic materials. The need for extensive characterisation effort is further complicated by the large number of variables associated with composite materials (fibre, resin, lay up, processing, etc.).

Despite these difficulties, numerical modelling is a useful tool in terms of the ability to compare the effect of experimental variables, key material properties and target variables on the response to blast loading. Throughout the UK research programme, an integrated experimental/modelling approach has been used to enable a greater understanding of the response of composite structures to mine blast loading. The potential contribution of finite element modelling to research and design can be summarised as follows:

- Enables rapid, low cost comparison of candidate materials (providing accurate material models are available)
- Assists experimental design (scaling, charge size, boundary conditions, etc.)
- Improves understanding of blast load/target interaction effects

Fig. 20 Predicted response of 28-mm carbon/epoxy laminate in flexible frame to blast loading by 1,000 g mine pot charge at (surface-to-surface) stand off distance of 520 mm



- Allows assessment of structural design factors (joints, corners, etc.)
- Optimisation of vehicle geometry to minimise the effects of blast on vehicle occupants

At present, modelling provides a rather conservative prediction of composite material performance against mine blast loading, due to the lack of accurate material failure data. Experimental assessment, therefore, is still a key to the weight-efficient design and development of composite vehicle structures.

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