# MODELLING AND EXPERIMENTAL INVESTIGATION INTO THE BALLISTIC BEHAVIOUR OF AN ULTRA HIGH MOLECULAR WEIGHT POLYETHYLENE/THERMOPLASTIC RUBBER MATRIX COMPOSITE

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**SUMMARY**: A finite difference modelling package was employed to determine the ballistic performance and the mechanisms of failure of a $0^0/90^0$ ultra high molecular weight polyethylene/thermoplastic rubber matrix composite. NATO standard ballistic testing was completed using fragment simulating projectiles for $4kgm^{-2}$ to $10kgm^{-2}$ laminates. The material model, developed at DCTA, when combined with an orthotropic equation of state and a mesh density of $17mm^{-2}$ yielded good correlation with the ballistic data. Post failure analysis, using optical microscopy and ultrasonic c-scan combined with the modelling have shown that the major failure modes for the laminate were: trans-laminar shear, delamination, and tensile failure along the yarn. The delamination size was investigated using an ultrasonic c-scan in the through transmission mode, which compared well with the modelling results. Stress wave investigation, using the model subsequently showed that superposition of elastic waves gives rise to delamination initiation. More than 50% of the energy absorbed by the laminate was due to transfer of momentum by the stress waves.

**KEYWORDS**: Ballistic materials, composite modelling, composite delamination, UHMWPE, ballistic testing, ultrasonic C-scan, composite tensile failure, fragment simulating projectiles.

## INTRODUCTION

The aim of this project was to validate modelling of the mechanical behaviour of selected materials, against fragmentation damage. The modelling was performed on a finite difference method hydrocode, called Autodyn-2D. The material modelled was Dyneema UD66 HB1 (an ultra high molecular weight polyethylene or UHMWPE composite), which has been used for fragmentation protection in body armour and helmets.

A material model was developed, at DCTA, to represent the mechanical behaviour of UHMWPE at ballistic strain rates. The model was used with Autodyn-2D to simulate the impact of a 1.1g stainless steel sphere onto a target plate. The modelling predicted the ballistic performance, the failure mechanisms and the post failure features of the material for a

number of areal densities. Experimental validation of the modelling was achieved by using a ballistic range, an ultrasonic C-scan and optical microscopes.

Comparison between the modelling and the experimental results was excellent for the ballistic performance of the materials. As micromechanical failure was not part of the material model, some of the experimental post failure features were not seen in the modelling. However, the major energy absorbers were identified and could be modelled. A large part of the kinetic energy of the 1.1g stainless steel sphere was absorbed by the transfer of momentum on impact. This was due to the creation and dispersion of elastic and shock stress waves.

## AUTODYN-2D MODELLING AND RESULTS

Autodyn-2D is a hydrocode which solves the fluid conservation equations of mass, momentum and energy within a discretised mesh. In order to simulate a solid a number of material relationships are required, these include:

1. Equation of state – relates the pressure, density and temperature of each discretised cell.
2. Constitutive equations – describe the stress/strain behaviour of the material. May also include inputting the yield surface of the material in Autodyn-2D.
3. Failure models – can include stress and/or strain to failure of a material.

The material model is found in table 1. Beside each constant there is the author reference for the mechanical property. The boundary conditions that have been used in the modelling are:

1. Optimisation of the mesh density, giving an average of 17 $mm^{-2}$.
2. Optimisation of the erosion model. The model discards a cell after a specified critical geometric strain. It increases the effeciency and stability of the code.
3. Using an axial symmetry to model the third dimension of the material.
4. Modelling the clamping frame that holds the specimen in the experimental ballistic range.
5. Optimisation of the information and rate of saving leading to give efficient use of computer time.

Table 1: The material model for Dyneema UD66 HB1

| | |
|---|---|
| LIBRARY: DCTA10 | MATERIAL: DYNEEM18 |
| | |
| | |
| **EQUATION OF STATE: Orthotropic** | |
| | |
| Reference density/$gcm^{-3}$: | 9.52000E-01 Frissen [2] |
| Youngs Modulus 1/kPa: | 4.50000E+06 estimated (Sharma, 1998) |
| Youngs Modulus 2/kPa: | 3.28000E+07 Frissen [2] |
| Youngs Modulus 3/kPa: | 3.28000E+07 Frissen [2] |
| Poissons Ratio 12: | 6.10000E-02 DSM [3] |
| Poissons Ratio 23: | 6.0000E-03 estimated (Sharma, 1998) |
| Poissons Ratio 31: | 3.0000E-01 estimated (Sharma, 1998) |
| Material Axes Option: | X-Y space |
| Reference Temperature/K: | 3.00000E+02 |
| Specific Heat (C.V.)/$Jkg^{-1}K^{-1}$: | 1.75000E+03 DSM [3] |
| | |

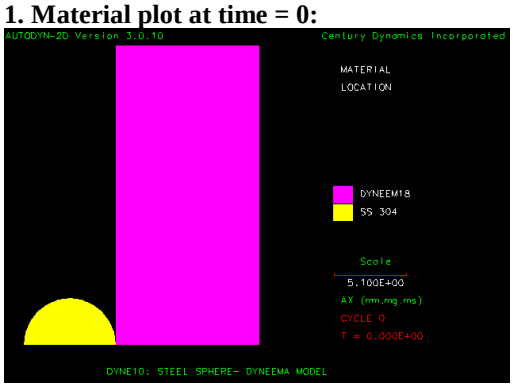
| | | |
|---|---|---|
| **STRENGTH MODEL: Elastic** | | |
| Shear Modulus/kPa: | 1.36000E+06 | Moyre *et al.* [4] |
| **FAILURE MODEL: Mat.Stress/Strain** | | |
| Tensile Failure Stress 11/kPa: | 8.00000E+04 | estimated (Sharma) |
| Tensile Failure Stress 22/kPa: | 2.70000E+06 | Morye *et al.* [4] |
| Tensile Failure Stress 33/kPa: | 2.70000E+06 | Morye *et al.* [4] |
| Maximum Shear Stress 12/kPa: | 1.60000E+05 | estimated |
| Tensile Failure Strain 11: | 2.40000E-03 | estimated (orthotropic equations) (Sharma, 1998) |
| Tensile Failure Strain 22: | 5.00000E-02 | estimated (orthotropic equations) (Sharma, 1998) |
| Tensile Failure Strain 33: | 5.00000E-02 | estimated (orthotropic equations) (Sharma, 1998) |
| Maximum Shear Strain 12: | 1.00000E-01 | estimated (orthotropic equations) (Sharma, 1998) |
| **EROSION MODEL: Inst. Geo. Strain** | | |
| Erosion Strain: | 5.00000E+00 | estimated (Sharma, 1998) |
| Reference: 7\2\98 Nikhil Sharma DCTA | | |

Experimental mechanical properties were used to formulate each model. When mechanical property data were not available, simple equations to predict the constants were used. Orthotropic equations were used to model some of the failure criteria. As described by Zukas [1], the failure model can define the perforation performance of a material. Hence the failure models were changed in order to accurately simulate the ballistic event.

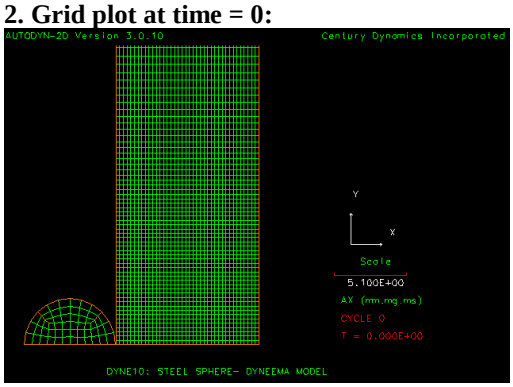
The orthotropic model developed was based upon data collected from DMTA work by Frissen (1996) and mechanical characterisation completed by Moyre [5]. In the present work, simple orthotropic equations were used to estimate the failure model. The shear stress and strain to failure were increased in order to simulate the ballistic performance of the materials.

Figure 1 shows the slide show for a 1.1g FSP sphere impacting a 10.2 $kgm^{-2}$ Dyneema UD66 HB1 plate at 800 $ms^{-1}$. Slide 3 shows that on impact the laminate fails by shear. At 10 microseconds (slide 4) delamination initiation occurs at the back of the plate. On impact, compressive longitudinal elastic stress waves are initiated; these are reflected off the back of the plate becoming tensile. These tensile waves superimpose with the oncoming compressive longitudinal waves and the shear waves to give tensile regions which act as the delamination initiators. At 16 microseconds (slide 5) the sphere has pushed the back face of the delaminations forward, increasing the size of the delaminations and hence allowing the kinetic energy of the 1.1g FSP sphere to be absorbed by the laminate. Slides 5 to 8 show the growth of the back face delamination, which was observed experimentally by Taylor [6]. Slides 7 and 8 show plugging from the back of the laminate, this was not observed by Taylor (1997).

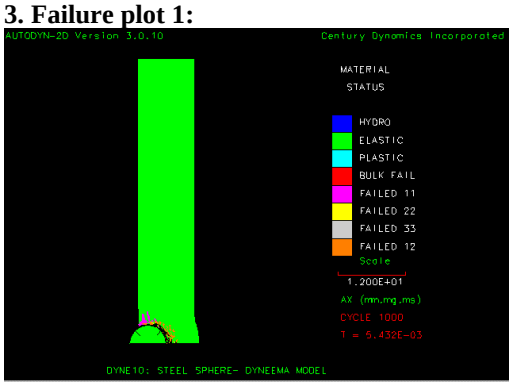
**1. Material plot at time = 0:**



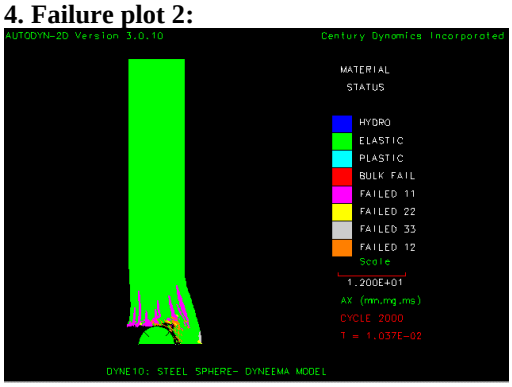

**2. Grid plot at time = 0:**



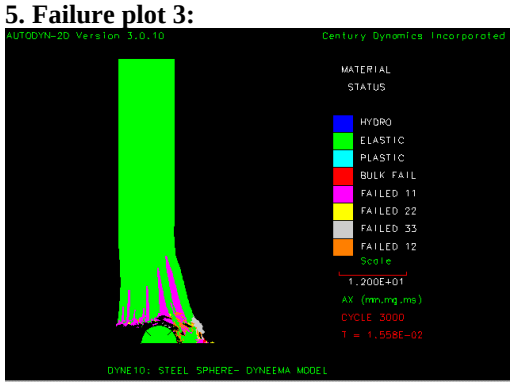

**3. Failure plot 1:**



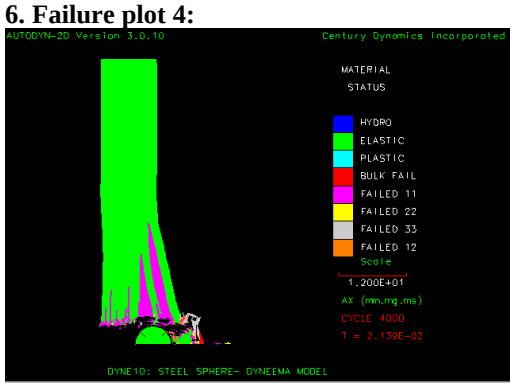

**4. Failure plot 2:**



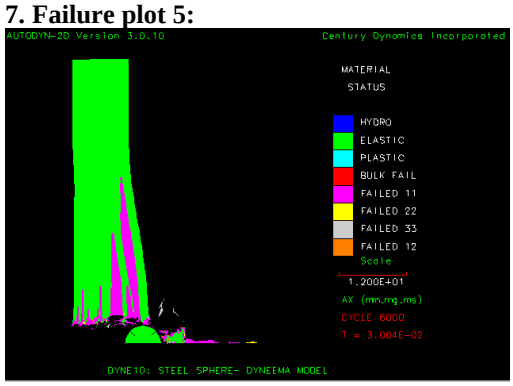

**5. Failure plot 3:**




**6. Failure plot 4:**




**7. Failure plot 5:**




**8. Failure plot 6:**

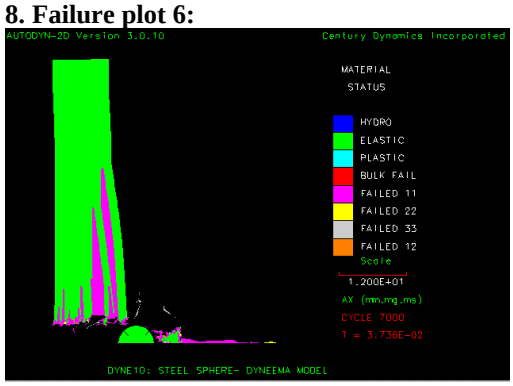



Fig. 1: 10.2kgm-2 Dyneema UD66 HB1 laminate struck by a 1.1g FSP sphere at 800ms-1 (failure plots)

Plotting the kinetic energy of the penetrator against time shows that about one half of the 1.1g FSP sphere energy is absorbed by the dissipation of the elastic stress waves. The remaining kinetic energy absorbed is by longitudinal tensile failure of the fibres and by delamination initiation and growth.

## EXPERIMENTAL PROCEDURE AND RESULTS

The appropriate quantitative data were selected from the experimental work to compare to the Autodyn-2D modelling presented in this paper.

### Sample preparation

The samples were prepared in order to match the methods used by the authors who had calculated the mechanical properties of the materials. The modelled material was hence physically as similar to the experimental samples as possible. The Dyneema UD66 HB1 was hot pressed from pre-impregnated laminates under manufacturer's instructions (DSM, 1997).

### Ballistic testing

The ballistic testing was performed in accordance with specification UK/SC/5449 (1996). The projectile used was a 1.1g fragment simulating projectile sphere. The ballistic indicator used was an estimated $V_0$.. For a particular projectile and material, the normal $V_0$ is the highest velocity below which it is estimated that there will be no perforations at all; the estimated probability of perforation is zero (Tobin, [7]). This is used to compare to the Autodyn $V_0$ (calculated from the kinetic energy plots of the 1.1g FSP sphere against time). A large specimen size was used to give the largest number of non-interacting shots, hence giving a low standard deviation of results. The equation used to calculate the was $V_0$ was:

$$normal\, V_0 = \sqrt{(V_s^2 - V_r^2)} \qquad (1)$$

where

$V_s$ = strike velocity

$V_r$ = residual velocity

This is assuming:

1. On perforation, the mass entering the sample is equal to the mass leaving the sample. However, the mass on exit can be estimated.

2. The target will not fail by differing mechanisms in the range of strike velocities.

For Dyneema UD66 (Fig. 2) the correlation is very good even when one considers the standard deviation of the experimental data (Autodyn-2D calculation error is less than 1%).

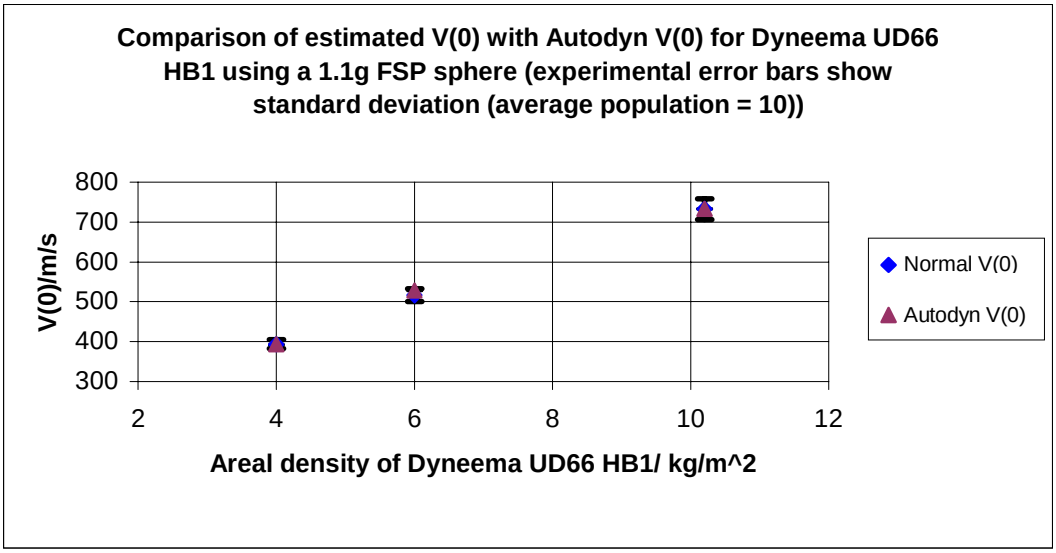



Fig. 2: Comparison between Autodyn-2D results and experimental results for a 1.1g FSP sphere impacting 4.0kgm$^{-2}$, 6.0kgm$^{-2}$ and 10.2 kgm$^{-2}$ Dyneema UD66 HB1

## Ultrasonic C-scan

The sizes of the largest deformation and delamination (the 'back face delamination') were measured post-failure, using ultrasonic C-scan in the through transmission mode (Meccasonics, Ross on Wye, Herefordshire, U.K.). Comparison was made between the diameters of the experimental and modelled back face delamination.

Fig. 3 shows an example of an ultrasonic C-scan of a Dyneema UD66 HB1 sample perforated by 1.1g FSP spheres. Notice that the dark areas are low attenuation and the light areas are high attenuation, where the waves are reflected and diffracted by the delamination defects.

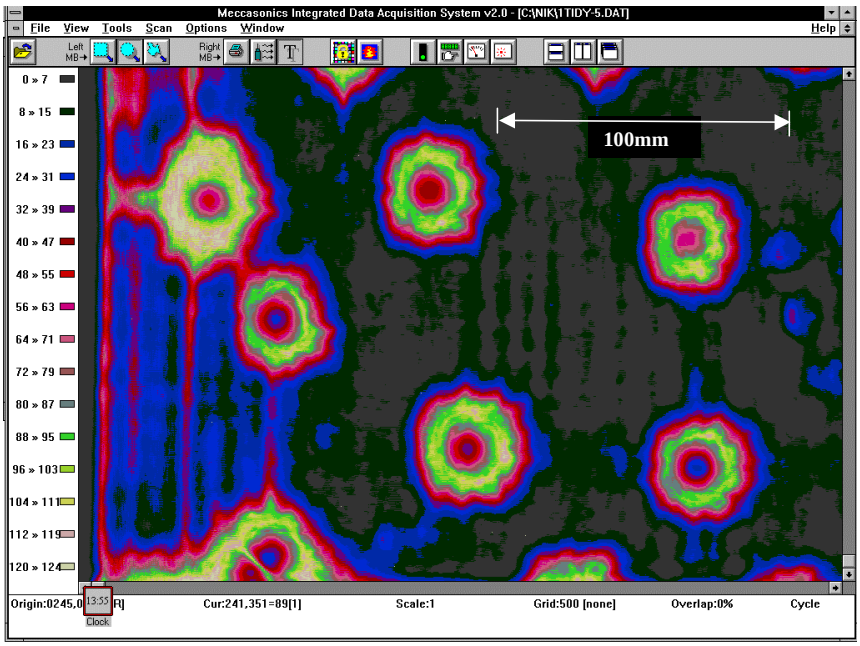



Fig. 3: C-scan for 10kgm$^{-2}$ Dyneema plate perforated by 1.1g FSP spheres

The diameters of the delamination can be measured using an elliptical overlay software tool. Fig. 4 compares the experimental results and Autodyn-2D calculations for the largest the back face delamination diameters of Dyneema UD66 HB1.

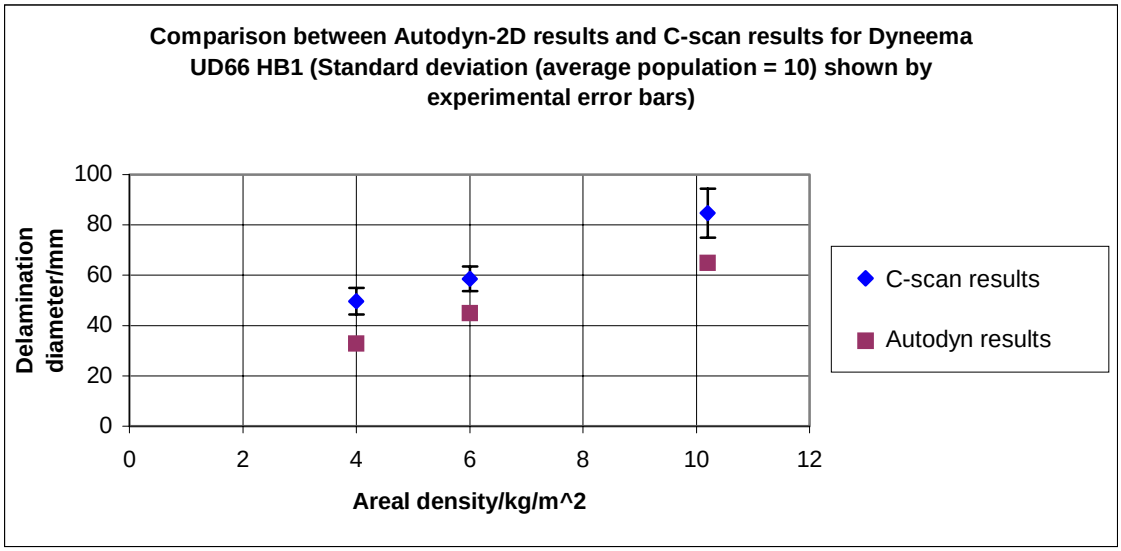



Fig. 4: Graph of delamination diameter from Autodyn-2D and C-scan results, for Dyneema UD66-HB1 perforated by a 1.1g FSP sphere

## Optical microscopy

The Leica lens system was connected to a JVC CCD camera which fed into a Data Translational PCI frame grabber to give both the failure features and the sizes of the entrance and exit holes of the samples. The post perforation holes in the Autodyn-2D modelling were measured for direct comparison.

Fig. 5 summarises the failure features for Dyneema UD66 HB1. These include fibre pull out, fibre failure, matrix failure, fibre pull off, delamination and elastic relaxation of the fibres and the matrix. Only the matrix/fibre failure and delaminations could be predicted from the modelling (Fig. 1). This is because Autodyn-2D considers Dyneema UD66 HB1 as a monolithic material as opposed to a composite made up of two materials.

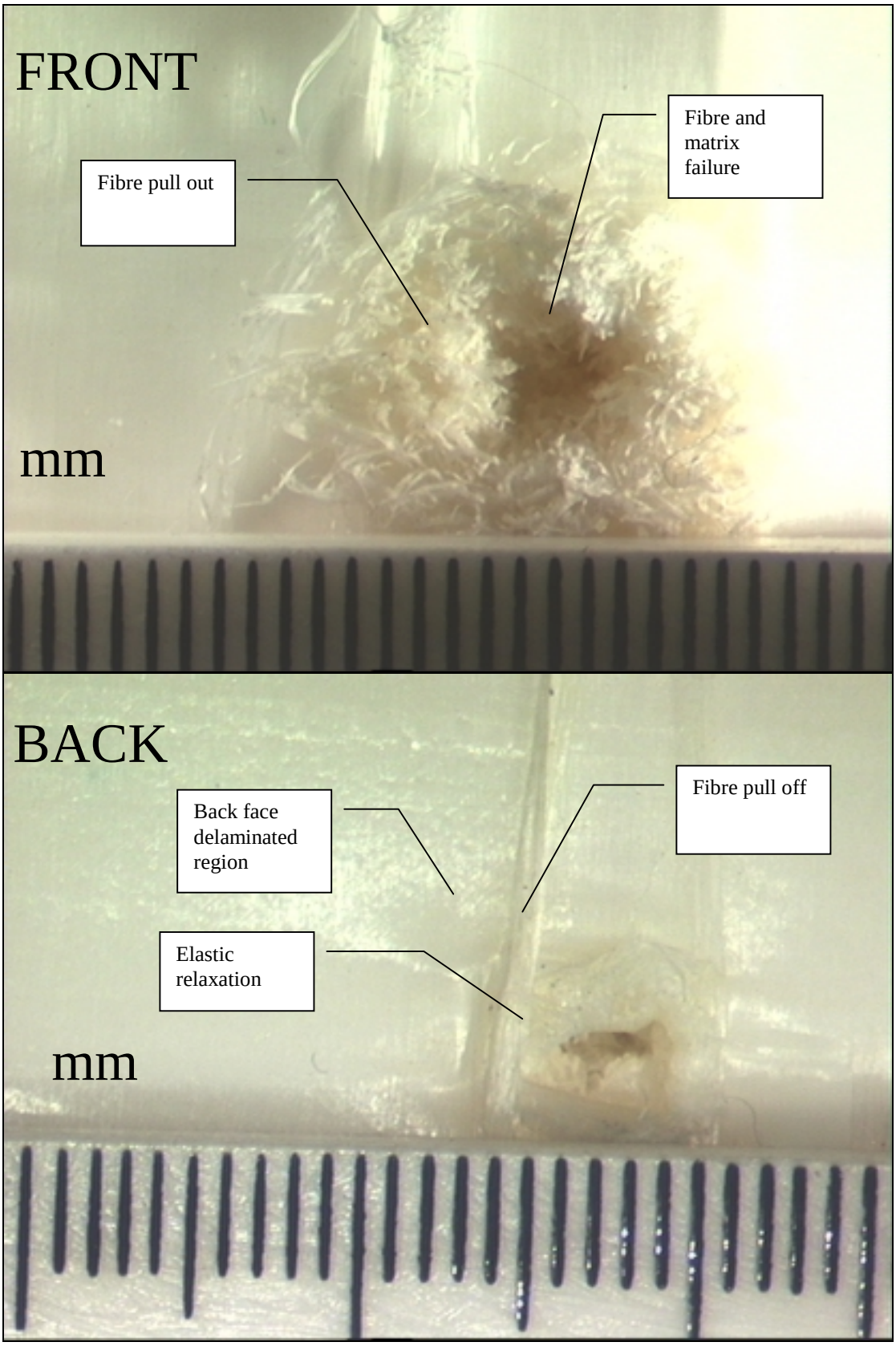



Fig. 5: Optical micrographs of 10.2kgm$^{-2}$ Dyneema UD66 HB1 laminate perforated by a 1.1g FSP sphere

## CONCLUSIONS

The ballistic events for a 1.1g FSP sphere impacting a number of thicknesses and areal densities were modelled for Dyneema UD66 HB1. The ballistic indicators compared well between the modelling and the experimental work. Post failure investigation using ultrasonic C-scan and optical microscopy showed that the micromechanical mechanisms of failure could not be modelled by Autodyn-2D. However, the modelling gave novel and complementary information about the material. The summary of the mechanisms of failure predicted by the modelling and the experimental work is given in figure 6.

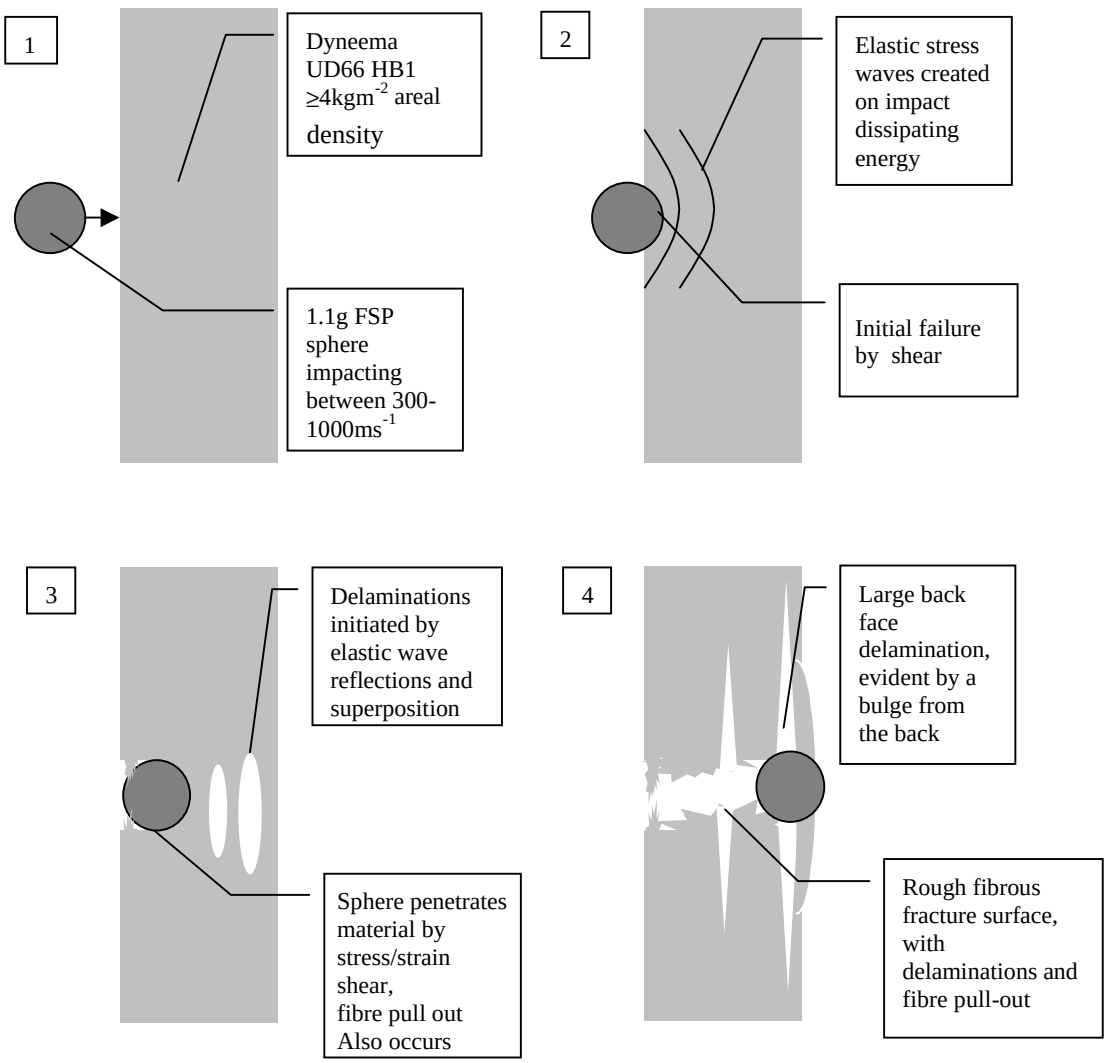



Fig. 6: Penetration mechanisms for Dyneema UD66 HB1 plate impacted by a 1.1g FSP sphere between 300ms$^{-1}$ and 1000ms$^{-1}$

In conclusion a model is only as good as the mechanical properties used for it. Due to the lack of consistent high strain rate mechanical data, it was difficult to separate the validation of the models developed by the author and the code. However, the work has brought us one step closer to replacing some of the very expensive experimental work performed at DCTA, S&TD ande may allow future consideration of novel systems

## ACKNOWLEDGEMENTS

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