IMPACT BEHAVIOUR OF LOW FIBRE-FRACTION GLASS / POLYESTER LAMINATES

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ABSTRACT

Instrumented falling weight impact tests have been used to study the impact behaviour of hand laid-up, low fibre-fraction, glass-fibre reinforced polyester laminates. The effects of laminate reinforcement and thickness, and of impact energy and velocity were studied. Failure modes were found to be complex, but a simple analysis assuming shear-dominated deformation enabled key features to be identified.

1. INTRODUCTION

Fibre reinforced plastics (FRP's) are now used in many applications in different fields of engineering. Advantages that have contributed to the recent increase in the use of FRP's include their high specific strength and stiffness, the ease with which complex shapes may be formed and their chemical and environmental resistance, amongst others.

However, a known weakness of these materials is their susceptibility to impact damage, especially transverse impact normal to the plane of the laminae. This potential weakness is due to the brittle nature of the reinforcing fibres, the lack of through thickness reinforcement, and the relatively low interlaminar shear strength of these materials.

The impact damage sustained usually consists of matrix cracking and degradation, surface micro-buckling, fibre fracture and internal delamination. The exact nature of this damage is dependent upon the nature of the composite and of the test specimen, and also upon the test geometry and conditions. The damage mechanisms are highly complex and interactive due to the nature of the microstructure of these materials, and extremely difficult to model.

Impact is an important issue in the marine industry due to the possibility of damage sustained during fabrication, for example the dropping of tools or collisions whilst moving or turning modules during assembly. Also, in-service damage may arise from regular minor impacts whilst docking, through the striking of floating objects in the water, to collisions with other vessels and grounding.

There is a wealth of literature on the impact behaviour of composite materials, and this literature covers many aspects of this complex composites testing area (see Abrate, 1998 for a comprehensive review). The great majority of this literature concentrates on expensive, high-quality, high fibre volume fraction carbon epoxy pre-preg laminates such as are commonly used in the aerospace industry. However, The bulk of the materials widely used in marine engineering are low fibre-volume, hand laid-up glass / polyester materials.

The huge differences between the budgets available for research in the aerospace and small craft industries mean that the structural behaviour of the latter type of laminates has received much less attention than the former. This often leads to the use of high and somewhat arbitrary safety factors in design.

The hand-made nature of these composites introduces considerable variation in these properties, further exacerbating the problem. Also, material properties may vary significantly with the almost limitless material combinations and laminate architectures available, and with the specific production methods and conditions.

This is especially true for impact properties and hence experimental evaluations are essential in this field. In this paper two such studies are described, one to investigate the nature of the impact behaviour of such materials, and the second to see how this behaviour is affected by the test set-up.

2. EXPERIMENTAL DETAILS

Panels of 1m by 1m were laminated by hand on a horizontal flat mould, and after cure specimens cut using a diamond-surrounded saw

The materials used were 500 and 800 gm^{-2} balanced woven roving (WR), and 450 gm^{-2} chopped strand mat (CSM) E-glass and polyester resin cured using 1%, 2% and 3% by weight of accelerator, catalyst and paraffin respectively. The resin used was isopthalic for the 500 gm^{-2} woven roving 5- and 10-ply specimens and orthopthalic for the rest of the specimens. The woven roving and chopped strand mat laminates were nominally of 50% and 33% fibre weight fraction respectively.

An instrumented falling weight impact test machine was used for the tests in this work. A controlled, repeatable impact is achieved by dropping a striker attached to a variable weight onto the sample in a defined manner and at a prescribed impact velocity. During the impact, the resistive force exerted by the specimen on the striker is measured by a load cell as a function of time, and stored for subsequent display and analysis. The software calculates, from the basic force-time information, velocity, distance and energy absorbed by the specimen.

There are three main parts to the falling weight apparatus, a tower where the weight falls onto the sample held below, a control unit, and the computer software system. The tower consists of a sample area, where a pneumatic clamp holds the sample, and a column down which an impactor head attached to a weight falls, guided by rails, onto the sample. (Figure 1).

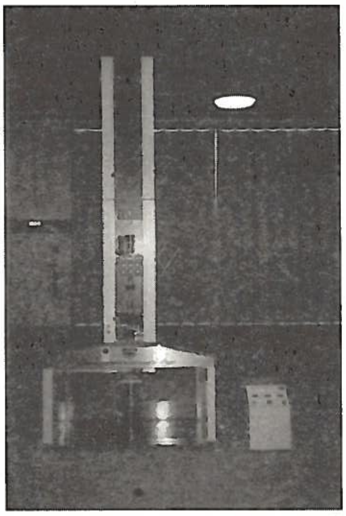

Figure 1: Falling Weight Impact Machine

The literature concerning carbon composites often inspects the damage sustained by the specimens after impact using ultrasonic C-scan methods. However the laminates considered here were translucent and it was possible to view the damage simply by backlighting the specimens. This gave the approximate damaged area, and also a qualitative description of the damage. Panels of 5, 10 and 15 plies were laminated using the 500 gm^{-2} WR to view the effect of thickness on the impact behaviour. To investigate the effect of reinforcement weight, 800 gm^{-2} WR was also used, 3 and 6 plies giving the nearest equivalent weights to the 5 and 10 ply 500 gm^{-2} WR panels. To include the behaviour of a different form of reinforcement, 450 gm^{-2} CSM was used to fabricate 5 and 10 ply panels.

Rectangular specimens of 100 mm by 150 mm were cut, for the woven roving specimens the warp was aligned with the longer dimension The specimens were clamped using a 'picture frame' clamp of dimensions 120 mm by 75 mm with the flat, mould side of the specimen facing down.

For each panel, tests were performed at 8 increasing incident energy levels, at both the highest and lowest velocities attainable within the constraints of the test machine. One repetition of each test was made, giving 32 tests from each panel, and a total of 224 specimens.

3. RESULTS

3.1 Wr Damage and Failure Modes

The damage sustained by the woven roving specimens may be grouped into three main categories; Front face buckling delamination under the impactor, internal shear delamination and back face matrix and fibre degradation.

The front face and internal delaminations were approximately circular for lower impact energies, but became progressively miss-shaped and elongated in the warp direction (the direction parallel to the long edge of the clamp) as the severity of impact increased. The back face damage consisted of a central area of matrix cracking and progressive degradation, and then associated fibre damage and failure at medium and high energies respectively.

As the highest energies were reached, specimen failure occurred either in the form of varying degrees of perforation of the specimen by the impactor, or by a line of shear failure from the centre of the specimen to the centre of the long edge of the clamp. The final failures of the 500gm^{-2} laminates were through perforation for the 5-ply specimens and through shear for the 10-ply specimens. Final failure of the 15-ply specimens was not seen. The 3-ply 500gm^{-2} specimens failed in shear (with the exception of one perforation), and the 6-ply specimens failed in shear and perforation in equal numbers.

Typical damage modes are shown in Figure 2 and Figure 3.

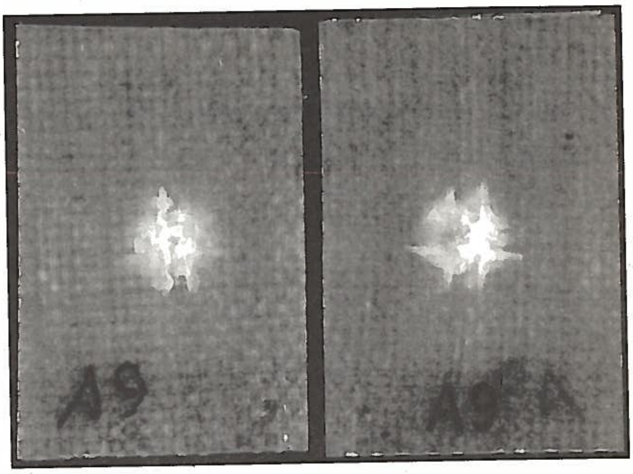

Figure 2: WR Specimen Low Energy Damage (Front and Back)

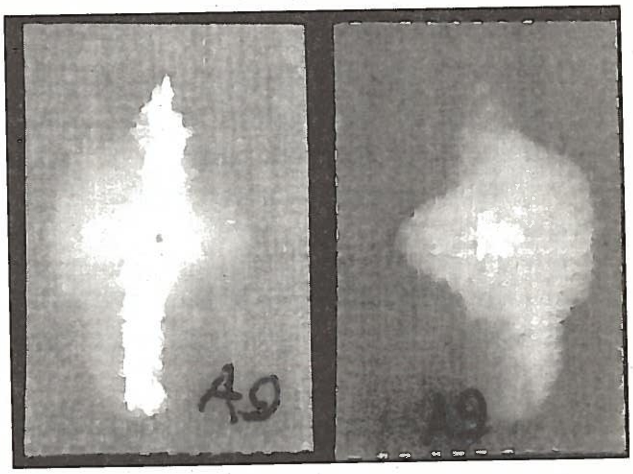

Figure 3: WR Specimen High Energy Damage (Front and Back)

3.2 CSM Damage and Failure Modes

As for the WR specimens, damage of the CSM specimens consists of front face damage, internal delamination and back face damage. However, in these cases the damage is slightly different (Figure 4). Also, final failure mode is exclusively perforation of the specimen by the impactor.

The front face damage initially consists of an annular area of delamination on the top surface that grows until it reaches the diameter of the impactor at around 30J and

90J for the 5- and 10-ply specimens respectively.

An indentation suddenly appears at 40J for the 5-ply specimens and at 115J for the 10-ply laminates. For the 5-ply specimens an apparent effect of velocity on the development of this front face damage can, on closer inspection, be seen to be due to thickness variability.

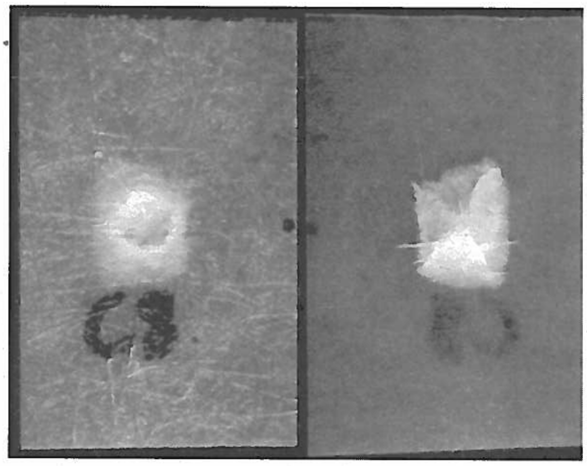

Figure 4: CSM Specimen Damage (Front and Back)

A small circular internal delamination at low energy elongates slightly, then becomes square or misshapen when perforation begins to occur. In the 10-ply specimens there are seen to be several internal delaminations, initially circular that grow to a certain size at 90J then remain at this size whilst the shape becomes more erratic

On the back face there is initially some central matrix cracks and detachment of fibres, and then when indentation occurs there is a ridge of fibre damage and splitting. Perforation is accompanied by a pyramid-shaped back face failure

3.3 Analysis

No discernable effect of velocity on the results was seen for the range of velocities considered here. Although some effects of velocity for the 5-ply CSM specimens were apparent, these were seen on further analyses to be due to a variation in thickness. The inherent variability of this material lead to a difference between the thicknesses of the specimens tested at the low and high velocities.

The relationship between the energy permanently absorbed by the specimen (mainly in the form of material damage) and the incident energy for all laminates is shown in Figure 5 and Figure 6.

There are two main bi-linear trends, one for the thinner laminates and one for the thicker laminates. Both show an initial section where the absorbed energy (AE) is approximately 2/3 of the incident energy (IE), followed by a second section where the slope increases to approximately 3/4. This change in slope occurs when the more severe, final failure damage modes start.

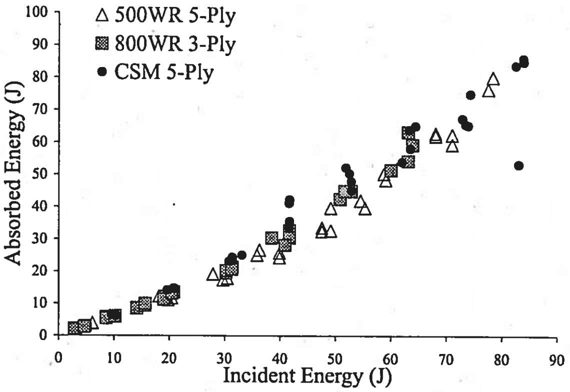

Figure 5: Absorbed Energy, Thin Laminates

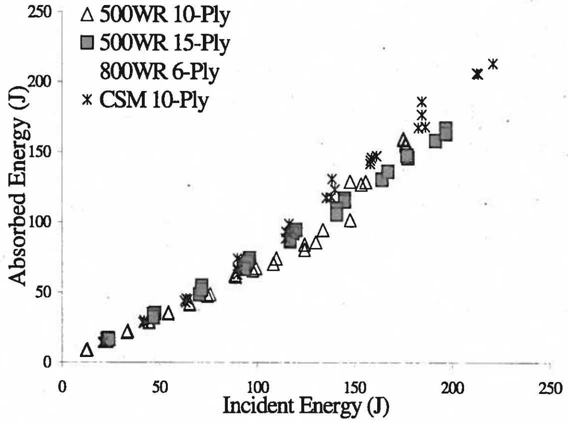

Figure 6: Absorbed Energy, Thick Laminates

Assuming that shear deformation dominates at the maximum deflection when the internal delamination exists (Zhou and Davies, 1995):

$$P_m = C_O t w_{Pm} \qquad (1)$$

where P_m is the maximum force, C_O is a material constant, t is the laminate thickness and w_{Pm} is the central displacement at the maximum force.

i.e.

$$w_{Pm} = \frac{1}{C_O}\left(\frac{P_m}{t}\right) \qquad (2)$$

Plots of w_{Pm} vs. (P_m / t) for the WR data give good linear correlation at lower energies. At higher energies, as back face damage leads to perforation, deviations from the line are clear for the 5-ply 500gm^{-2} WR specimens (Figure 7). Although not as marked, deviations are also seen at the highest energies for the equivalent 10 and 15-ply specimens.

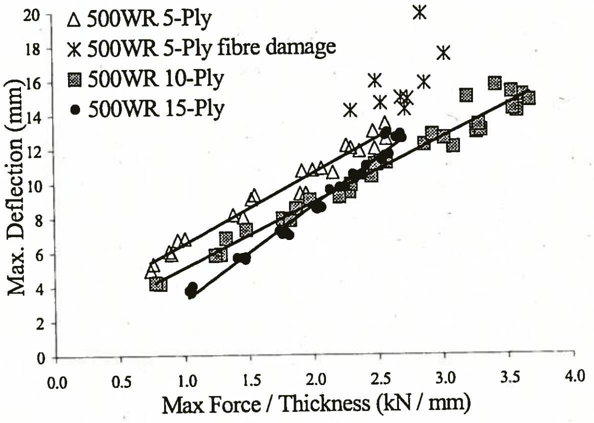

Figure 7: Eqn. (2): 500gm^{-2} WR Data

The final failure of both the 3 and 6-ply 800gm^{-2} specimens are clearly seen in Figure 8.

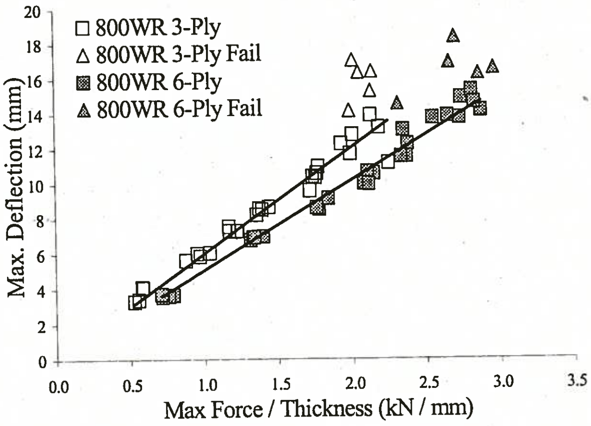

Figure 8: Eqn. (2): 800gm^{-2} WR Data

For the CSM specimens indentation is much more important. Although an initial linear section is present at low energies, significant deviation from the theory is seen as indentation and then perforation occur (Figure 9).

When the maximum deflection is reached, the incident kinetic energy (IKE) can be equated to the work done:

$$IKE = \frac{1}{2}mv^2 \approx \alpha P_m w_m \qquad (3)$$

where α is a 'shape factor' for the force deflection curves.

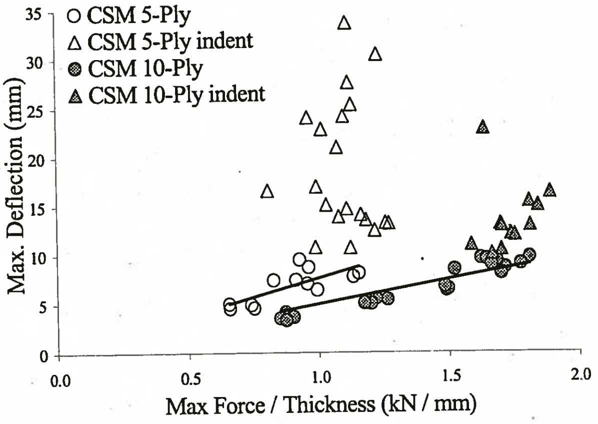

Figure 9: Eqn. (2): 450gm^{-2} CSM Data

Assuming that the force deflection curves are of approximately the same form, and that the maximum deflection is approximately the same as the deflection at the maximum force, equations (1) and (3) give the maximum force as a function of incident energy:

$$\frac{IKE}{t} = C\left(\frac{P_m}{t}\right)^2 \qquad (4)$$

where C is the constant α/C_O.

Plotting the 500 gm^{-2} WR data as per this equation again gave strong linear relationships. (Figure 10).

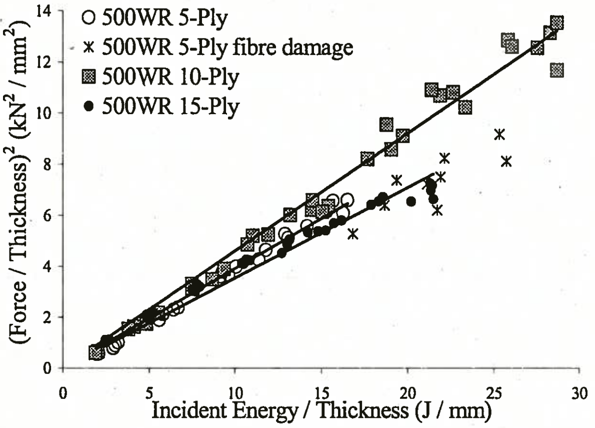

Figure 10: Eqn. (4): 500gm^{-2} WR Data

Perforation of the 5-ply specimens is again evident, but not as clearly as in Figure 7. Some deviation from the line at higher energies for the 15 ply data could indicate that more severe, but unseen, damage is present. However, the 10-ply data final shear failures are not visible in this plot.

Strong linear relationships and clearly indicated final shear failures are shown in the equivalent plot for the 800 gm^{-2} WR data (Figure 11).

Further details of this study may be found in Sutherland and Guedes Soares 1999.

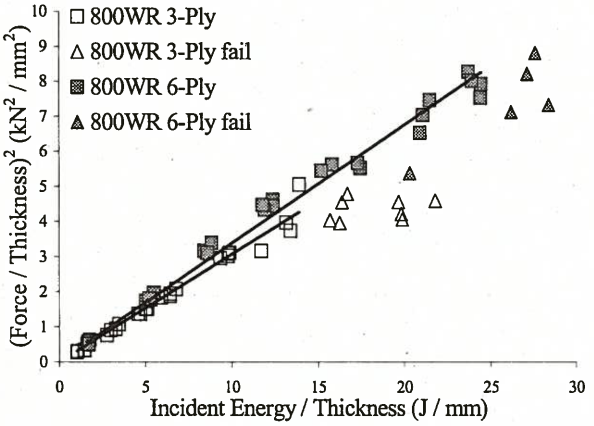

Figure 11: Eqn. (4): 800gm^{-2} WR Data

The onset of indentation can be clearly seen for the CSM laminates in Figure 12. Possibly this plot could be used to more revise the definition of the beginning of more severe damage for the 10-ply currently assessed visually.

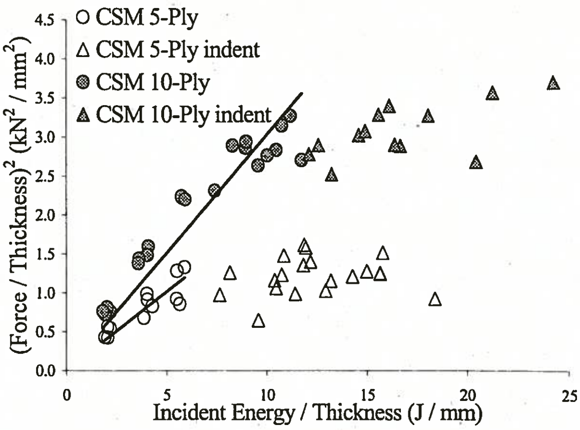

Figure 12: Eqn. (4): 800gm^{-2} WR Data

4 CONCLUSIONS

The damage modes sustained by the composites studied here were seen to be complex. Damage, in the form of internal delaminations occurred even at very low incident energies. Permanent indentation was important for the chopped strand mat reinforced laminates, and this is thought to require further investigation. At higher incident energies more severe damage modes are initiated in the form of back face fibre fracture leading to perforation or shear failure of the specimen.

The onset of more severe damage can be seen from plots of the energy irreversible absorbed by the specimens. A simple energy balance approach assuming shear-dominated deformation gave good correlation at lower energies and also allowed identification of the onset of final failure modes.

Current work investigating the effects of test parameters has shown that the impact behaviour and damage modes of such composites are strongly dependant on the test set-up. This indicates difficulties in the interpretation and scaling-up of test data to the full-scale. The scaling issue needs to be addressed, and hence future work includes impact of larger, panel-scale laminates.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

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