Impact on marine composite laminated materials

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ABSTRACT: This paper presents an overview of an extensive, mainly experimentally based, study of the impact response of marine composite materials carried out over the past several years. The work has investigated the progression of damage modes with increasing incident energy, the effects of test and material properties, the contact indentation, comparisons between common marine laminates and with steel and marine grade aluminium, scaling effects, and suitability of the use of quasi-static tests to obtain dynamic the response. This work has provided a wealth of important information on the impact behaviour of the material systems used in the marine industry, and hardly touched upon in the existing literature. Although numerical modelling techniques may be helpful, an experimental approach is essential. Some recommendations when carrying out such experimental studies have been made.

1 INTRODUCTION

Laminated composite materials are known to be vulnerable to transverse impact damage, arising from such varied events as collisions, striking floating debris, grounding, docking or objects dropped on board during operation or fabrication. Impact damage may be dangerous not only because a breach may lead directly to a loss of the structure at sea, but also because less severe damage may leave the structure unable to support a future unusual load that would be normally within the design limits. Also, damage may grow with the cyclic loadings ubiquitous in the marine environment possibly eventually leading to a catastrophic failure under normal loading. These points are especially dangerous since damage may well be internal and remain undetected.

The impact of a composite material is a highly complex problem, due to the following points:

- It is a dynamic event,
- The impact event itself is defined by many variables such as impactor and target geometries, impact velocity and energy.
- There are many interacting damage modes,
- The damage modes and paths are very sensitive to changes in the huge number of material and impact scenario permutations available,

Hence what is meant by the 'impact response' of a composite material is very difficult to standardize.

A large amount of research into impact on composites has been completed; the reviews of Cantwell and Morton (1991), Richardson and Wiseheart 1996), Bibo and Hogg (1996), Abrate (1998), Reid and Zhou (2000), Elder et al (2004), Resnyansky (2006a, b), and Bartus and Vaidya (2007) between them provide well over 1500 references.

However, the complexity of the problem, as described above, together with the large range of impact geometries and material systems studied has meant that this huge body of work is very difficult to standardise, and many aspects remain unclear and/or comparisons between different studies are difficult.

Further, these studies almost exclusively concern high-cost laminates as used in the aerospace industry - mostly high fibre-fraction, autoclaved pre-impregnated carbon fibre / epoxy, whereas in the marine industry much lower fibre-fraction, hand-laminated E-glass / polyester laminates are much more common.

To date far less attention has been paid to the impact of these lower-cost 'marine composites', and hence large safety factors (either explicit or implicit) are often required to allow for possible impact events (Mouritz et al 2001). Experimental work at DNV, considered the oblique impact on single-skin and sandwich high- speed craft hull lay-ups (Wiese et al 1998, Aamlid 1997). The penetrating impact of marine composites was studied at VTT, mostly of sandwich panels (Hildebrand 1996), but also comparing single-skin laminates with plywood, aluminium and thermo-plastics (Hildebrand 1997). Notably, it was found that, since different rankings were obtained for various lay-ups for each of three different test methods considered, it was not even possible to make qualitative comparisons between the results of different test methods. Impact on marine composites was studied at IFREMER (Collombert et al 1998, Davies et al 1998), though much of the work was industrial, particularly for the oil industry, and confidential.

All of the common impact events mentioned earlier may be described as low velocity impacts. This means that through-thickness stress wave effects are not significant and that damage arises after the target has begun to move. For analysis purposes the impact event is usually split into two parts, localised contact and overall target deflection (Figure 1).

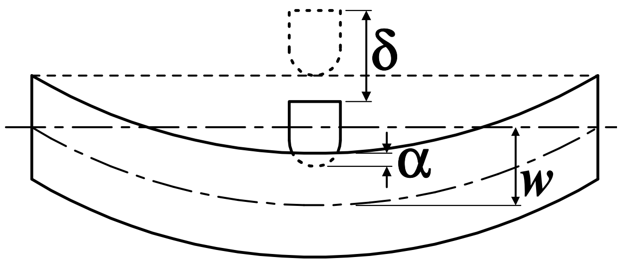

Figure 1: Displacement (δ), Indentation (α) and Deflection (w)

Surface indentation is normally assumed to follow the Hertzian contact law (Tan & Sun 1985). Complete models exactly describe the deformation of the target using beam or plate theories or finite element modelling (Chen & Sun 1985, Naik et al 2000) for simple cases for small deflections and simple material architectures. However, these complex models rapidly become extremely convoluted when more complex architectures, large deflections, membrane effects or significant shear deformations must be considered.

Most significantly, they are not effective for the consideration of the many (and interacting) damage modes invariably seen. Hence, theories to describe the overall response, such as the energy balance and spring-mass methods (Abrate 2001) are more realistic.

Work in the area at CENTEC, Instituto Superior Técnico commenced with a theoretical study (Carvalho & Guedes Soares 1996) which compared a numerical formulation with an analytical solution of the response of a simply-supported T300/934 carbon-epoxy composite plate70 subjected to an impact load. Both solutions utilized the technique of Fourier series expansion for the solution of the dynamic plate equations. The numerical solution utilized the Newmark integration method to solve the non-linear integral equation. The analytical formulation adopted the Laplace transform technique, requiring a linearization of the contact deformation. The contact force, displacement and strain results of the two theoretical methods were compared for a squared and a rectangular plate.

Following this initial theoretical work, an extensive, mainly experimentally based study of the impact response of typical marine composites was developed. In this paper an overview of this, ongoing work is presented.

2 EXPERIMENTAL DETAILS

Various combinations of Woven Roving (WR) and Chopped-Strand Mat (CSM) E-glass and WR Kevlar reinforcements, with (iso- and orthophthalic) polyester and epoxy matrices have been considered. However, most of the work presented here concerns E-glass / polyester laminates, and unless otherwise stated, the results quoted refer to this material combination. Composite panels of various thicknesses (2 to 20mm) were laminated by hand on horizontal flat moulds. Fibre mass-fractions of 0.5 and 0.33 for WR and CSM respectively (approximately equivalent to fibre volume fractions of 0.35 and 0.2 respectively) were specified as representative of the values commonly achieved under production conditions in the marine industry. Specimens were then cut from the panels using a diamond-surrounded circular saw. In order to ensure a full cure, specimens were stored at room temperature for a number of months before testing. Thickness measurements were taken at four points on each specimen prior to testing.

Impact testing was performed using a fully instrumented Rosand IFW5 falling weight machine (Figure 2). A small, light hemispherical ended cylindrical impactor head is dropped from a known, variable height between guide rails onto a clamped horizontally supported plate target. A much larger, variable mass is attached to the impactor and a load cell between the two gives the variation of impact force with time. The data may be post-filtered to remove noise from the signal. An optical gate gives the incident velocity, and hence the impactor displacement and velocity and the energy it imparts are calculated from the force-time data by successive numerical integrations.

Since the impactor is assumed to remain in contact with the specimen throughout the impact event, the impactor displacement is used to give the displacement and velocity of the top face of the specimen, under the impactor. By assuming that frictional and heating effects are negligible, the energy imparted by the indenter is that absorbed by the specimen. Thus, this energy value at the end of the test is that irreversibly absorbed by the specimen.

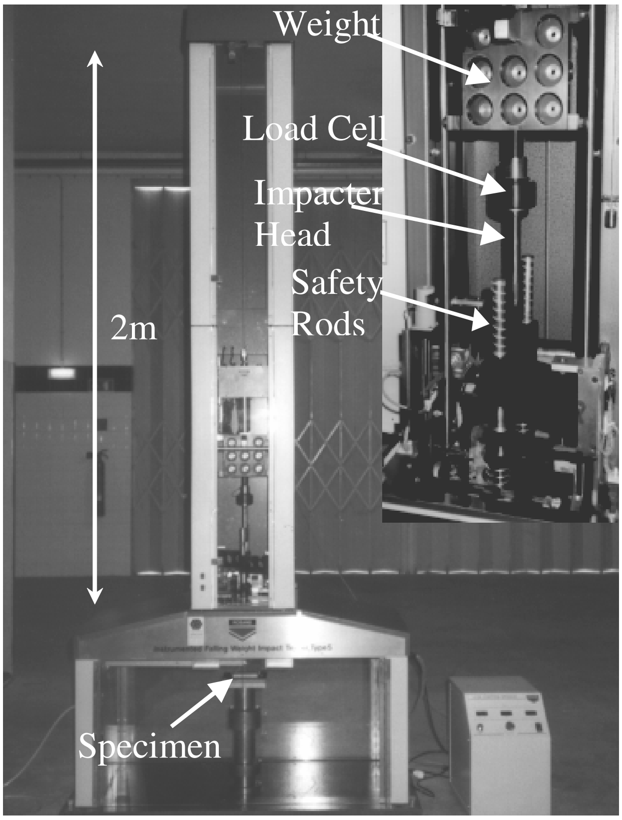

Figure 2: Instrumented falling weight impact machine

The specimens were fully clamped between two thick rectangular 'picture frame' (120 x 75mm) or annular circular (50 to 300mm diameters) steel plates. The exact clamping method used was seen to influence the results (Sutherland & Guedes Soares 2003, 2005a). 10, 20 or 30mm diameter impactor heads were used. Tests were carried out on nominally identical specimens to give families of results at increasing levels of incident energy. A catching mechanism ensured that rebounds did not lead to repeated impacts.

3 IMPACT BEHAVIOUR

From the earliest experimental work (Sutherland & Guedes Soares 199a) the impact behaviour was seen to be complex, involving various interacting damage modes. Hence the progressive characterisation of this behaviour has formed an integral part of the work [Sutherland & Guedes Soares 1999b, 2002, 2004, 2005a, b, c, d, 2007a].

The most important point noted is that damage occurred *at all but the very lowest incident energies*. Damage modes were both multiple and complex, including matrix cracking, matrix degradation, permanent indentation, internal delamination, partial surface micro-buckling delamination of the upper 'front-face' laminate, front-face fibre damage, fibre damage on the lower 'back-face', and perforation. These modes form a complex overall damage pattern, but the progression of damage with increasing incident energy is similar for all specimens, and may be categorised into three regimes (Sutherland & Guedes Soares 2005a):

- *'Un-delaminated'*: At extremely low incident energies damage is slight and mainly restricted to matrix cracking.
- *'Delaminated'*: At a low critical incident energy delamination suddenly occurs, which then spreads with increasing impact severity.
- *'Fibre Damage'*: At higher energies fibre failure occurs, leading to perforation.

However, differences in damage were seen between 'thin' and 'thick' specimens (the divide in this case was a diameter to thickness ratio of around 15) as illustrated in Figure 3 and Figure 4 (where the front-face is shown above the back-face).

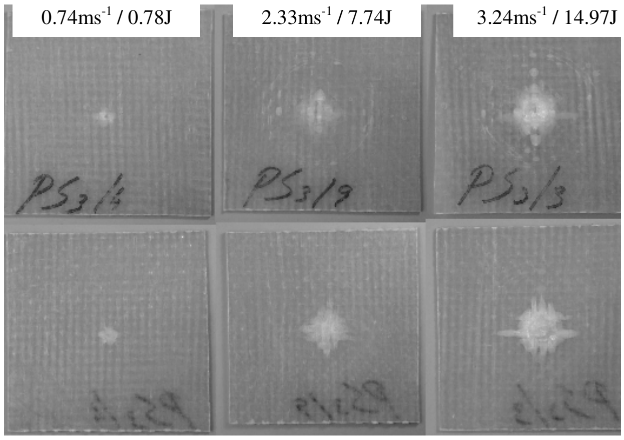

Figure 3: Impacted Thin Circular Clamped Laminates

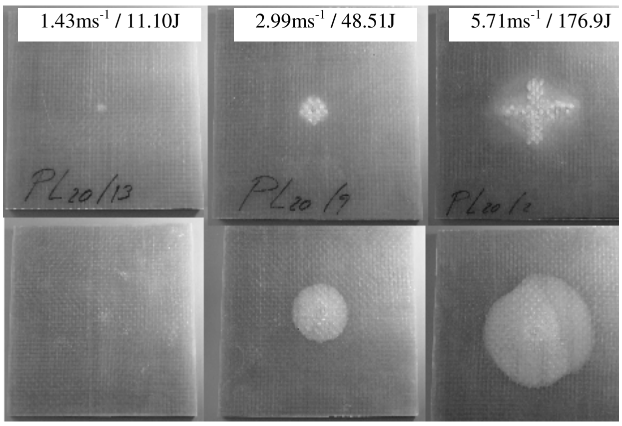

Figure 4: Impacted Thick Circular Clamped Laminates

The thickness to plate diameter ratio may also be interpreted in terms of the distance between impact and stiffener. The behaviour of thick laminates would correspond not only to that of thicker panels, but also to that of thinner panels where the impact occurred near to a stiffener.

The thinner specimens incurred less internal delamination, but were more prone to back face fibre damage, whereas indentation damage was greater for the thick specimens. The impact response also differs between thin and thick specimens as shown in the force-displacement and force-time plots of Figure 5 and Figure 6. Each graph shows a family of curves for increasing incident energy.

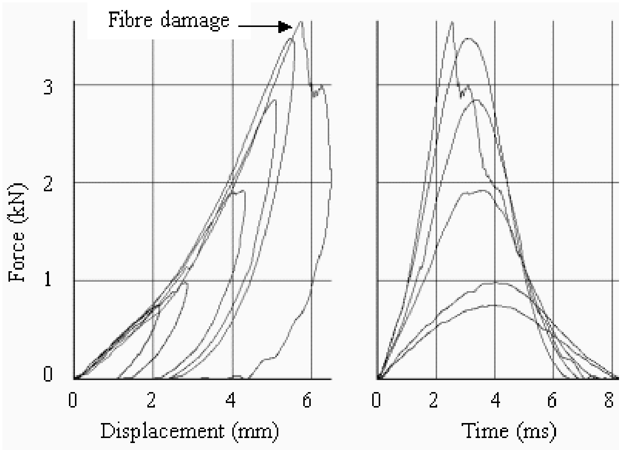

Figure 5: Impact Response Thin Laminate

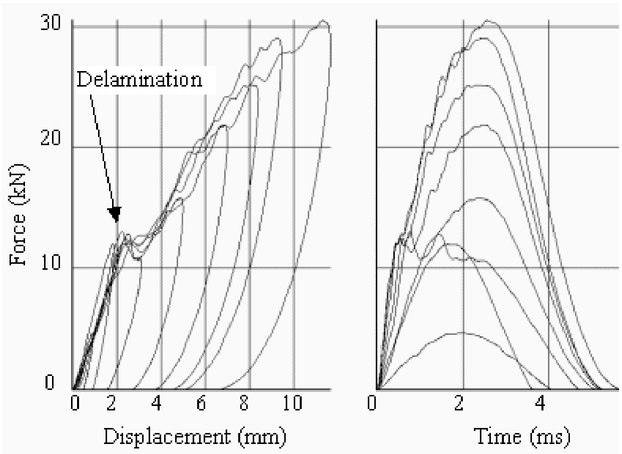

Figure 6: Impact Response Thick Laminate

Thinner laminates show the increase in stiffness with displacement due to membrane effects until fibre damage gives a sharp drop in force. Thicker laminates show a bi-linear response due to the onset of internal delamination. Despite the fact that internal delamination also occurred in the thinner laminates, no effect of this on the response is seen in Figure 5

A typical plot of absorbed energy with incident energy is presented in Figure 7, where fibre damage is indicated by a dotted symbol. Here, approximately 75% of the incident energy is irreversibly absorbed until fibre damage absorbs more energy. Hence, even at the lowest incident energies a significant amount of the incident energy is absorbed, although no delamination has occurred. Whether this is due to hidden damage such as matrix micro-cracking, or due to other mechanisms such as friction or visco-elastic effects is not clear. The onset of delamination is not reflected in this plot. For the thicker specimens at higher incident energies increased indentation damage causes the points rise above the 75% line before fibre damage occurs.

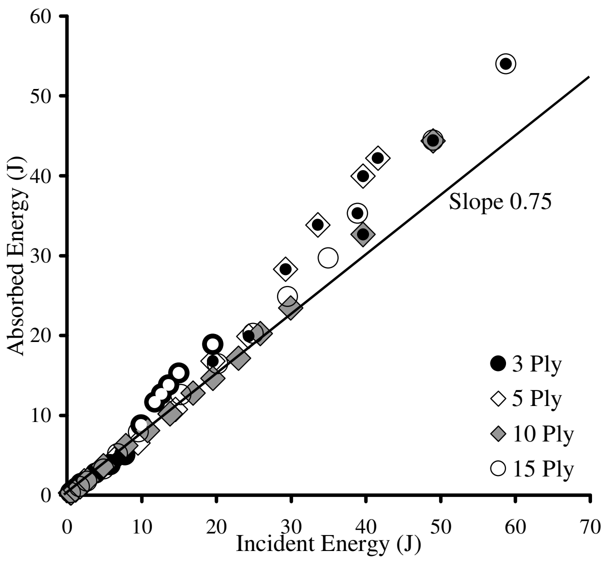

Figure 7: Irreversibly Absorbed Energy, 50mm Diameter Circular Specimens.

4 TEST AND MATERIAL PARAMETERS

One of the main problems with the standardisation and interpretation of impact response is the dependence of the behaviour on the test set-up / impact event. A study using statistical experimental design techniques (Sutherland & Guedes Soares 2003) investigated the effects of clamp geometry (square or circular), clamping surface (flat steel or with sand paper), and impactor head (hemispherical or flat ended), all at both low and high incident energies.

It was not only found that all parameters had significant effects on the impact responses, but also that the size of the effect of each parameter depended on the values taken by the other parameters and on the severity of the impact event. In some cases the effect of one parameter was reversed when another parameter was changed. This was usually due to the fact that changes in test parameters often led to slight differences in failure modes.

Further, the effect of a given parameter often differed depending on whether the impact response was quantified in terms of force, deflection, absorbed energy or damaged area.

This work did not claim to have answered all the questions, but rather illustrated that statements such as, for example, that a hemispherical impactor head will give more or less damage than a flat one, are over-simplistic – whether or not this is true will depend in a complex way on all the other test parameters.

For composite materials this aspect is further complicated because the impact response will also depend on the exact combination of the huge number of available material and production variables considered.

The work has investigated the effects of some of the more common material parameters. Different laminators were used to replicate panels to investigate the effect of laminator (Sutherland & Guedes Soares 1999a). No significant effects were seen, although all of the laminators used were inexperienced and were working under laboratory conditions.

The choice of iso- or orthophthalic polyester resin was found to be far less important than the amount of crimp in nominally identical weight E-glass WR reinforcement (Sutherland & Guedes Soares 2005c). Epoxy / glass laminates gave less internal delamination, but more back-face fibre damage than equivalent polyester / glass laminates (Sutherland & Guedes Soares 2005b).

5 INDENTATION

The indentation of the impactor into the surface of the laminate may be significant; for stiffer plates this may contribute significantly to the total measured impactor displacement. Although Surface indentation is normally assumed to follow the Hertzian contact law (Tan & Sun 1985), indentation tests carried out on marine composites by the authors (Sutherland & Guedes Soares 2005e) show that the actual response for these materials is more complex.

Quasi-static indentation tests on low fibre-volume, hand produced, E-glass (both chopped-strand mat and woven roving) / polyester 'marine' laminates have been performed. Hemispherical ended cylindrical indenters of diameters 10, 20 and 30mm were pushed down onto the surfaces of the fully supported laminated plates using a servo-hydraulic test machine, and the resultant indentor force and deflections recorded with time.

A Hertzian contact law described well the initial response (Figure 8), but the increase in stiffness with indenter radius was not well described by the theory. Obtaining the power law parameters was extremely sensitive to the initial few data points, where the presence of an irregular resin-rich surface was influential.

At higher loads the response became linear as damage became significant (Figure 8). The transition to linear behaviour is thought to be due to delamination and was not sensitive to reinforcement type.

Good correlation of the transition load with indenter radius was obtained using a simplified shear delamination model (Figure 9). This contact induced delamination is thought to be significant in terms of the complex impact damage progression seen in cocurrent work.

The slope of the linear response increased approximately linearly with indenter radius, and was not sensitive to reinforcement type. The highly complex mechanisms responsible for this behaviour are thought to involve damage progression under a complex stress field and require further investigation.

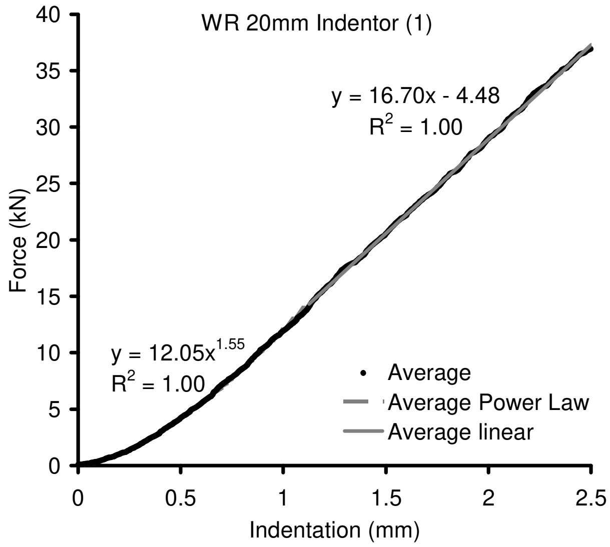

Figure 8: Typical Power Law and Linear Response

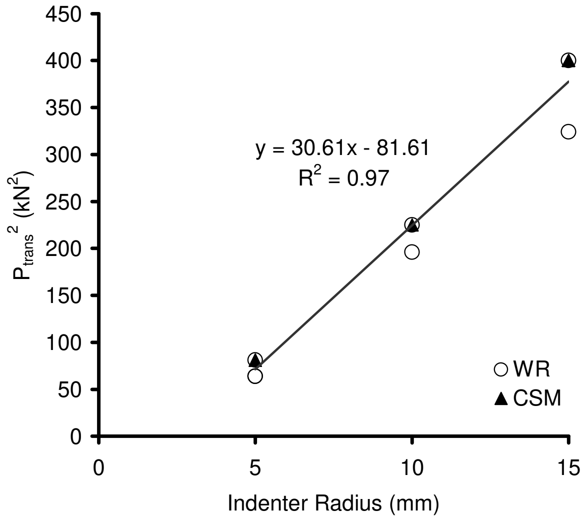

Figure 9: Transition to Linear Contact Response

Despite their significantly lower fibre-volume, chopped strand mat laminates exhibited a slightly higher contact stiffness than woven roving laminates. The tests were very repeatable, but considerable material variability was seen in the Hertzian behaviour of the woven roving tests due to the especially variable nature of this material.

6 LAMINATE COMPARISONS

The impact response of five types of laminate has been compared experimentally; WR, CSM, alternating WR/CSM, WR with the impacted top ply substituted with a Kevlar ply (Kevlar/WR), and WR with the back-face ply substituted with a Kevlar ply (WR/Kevlar) (Sutherland & Guedes Soares 2006).

Thin and thick 100mm diameter fully clamped specimens were impacted with a 20mm diameter hemispherical ended impact head. In order to make meaningful comparisons the different laminates were designed to be of equal stiffness.

For both thick and thin plates, at incident energies where no fibre damage occurred there was very little effect of laminate lay-up on the impact response. Delamination of all laminates occurred at very low incident energies, which were not dependant on laminate type. A small initial surface delamination occurred (thought to be due to contact forces), followed by a deeper and larger internal delamination due to global plate stresses.

At higher incident energies damage trends were again complex, but overall fibre damage was most severe for CSM and CSM/WR laminates. The laminates of WR and of WR with an upper Kevlar layer were consistently more resilient to fibre damage, but there was no significant difference between their respective impact responses.

The impact behaviour seen is summarised in Table 1. The complexity of this behaviour, and its sensitivity to the exact nature of the impact event, shows that the definition of the impact behaviour of a laminate must be correspondingly comprehensive.

	Thin Laminates	**Thick Laminates**
Un-Delaminated	65% Incident Energy irreversibly absorbed	
Delaminated	Started at same IE for all laminates	
	Area << Thick Laminates Slightly smaller for CSM 65% IE irreversibly absorbed	Area >> Thin Laminates 80% IE irreversibly absorbed
Fibre Damage	Back-face occurred first WR/Kev & CSM first to suffer Resistance to fibre damage: WR & Kev/WR > WR/Kev > CSM/WR >> CSM CSM damage generally smaller CSM/WR damage largest	Front-face occurred first 10mm ∅ impactor: onset fibre damage independent of laminate 20mm ∅ impactor: CSM & CSM/WR first to suffer Resistance to fibre damage: WR, Kev/WR & WR/Kev >> CSM/WR > CSM CSM damage slightly smaller

Table 1: Summary of Impact Behaviour of Different Laminates

Current work (Sutherland & Guedes Soares 2009) compares the impact responses of WR & CSM with those of steel and Aluminium (5083) plates. Again thin and thick 100mm diameter fully clamped specimens were impacted with a 20mm diameter hemispherical ended impact head. Equivalent plate stiffness was aimed for, but since only certain metal plate thicknesses were available corrections had to be made to enable valid comparisons to be made.

The perforation of metal plates occurs at much higher incident energies than for the composite materials. However, behaviour up to perforation was more complex.

For thick plates the maximum force was very similar up to perforation for all plates, with only the CSM giving a lower force as fibre damage occurred. The energy absorbed was lower for the composites (especially for WR) until fibre damage occurred.

For thin plates behaviour for Aluminium and composite plates was very similar, with steel giving higher maximum forces and lower maximum displacements. However, the energy absorbed was very similar for all materials.

Detailed information of the impact response of the aluminium plates has been obtained through non-linear explicit dynamic simulation using the LS-DYNA software package (Villavicencio et al 2010). The results obtained were in good agreement with those of previous experimental tests, indicating that even computationally inexpensive coarse meshes using shell elements are sufficient to predict the maximum deflections and forces.

However, finer meshed shell and solid element models give better and best prediction of the force-displacement behaviour, respectively. Where small discrepancies between numerical and experimental results occurred, this was due to overestimation of the impact force; the variation of displacement with time is generally very well predicted.

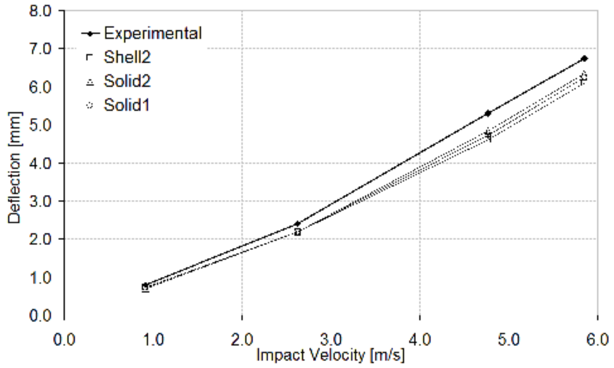

Figure 10: Maximum deflection vs. impact velocity. Thick (5.92 mm) circular plates.

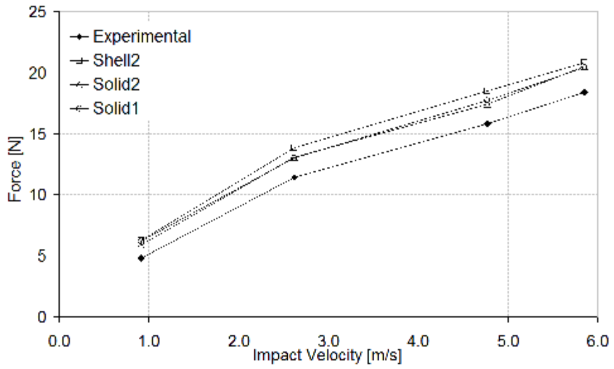

Figure 11: Maximum force vs. impact velocity. Thick (5.92 mm) circular plates.

The numerical simulations give a good understanding of the shape of the deformation in plates subjected to impact loading, and a fine meshed solid model is needed to give a good approximation of the deformation shape, especially where local indentation is significant.

The material true stress-strain curve inputs to the numerical model were obtained from tensile tests on the actual material used to fabricate the impacted plates.

The numerical models were successfully used to predict the impact response of Aluminium 5083 plates, and the next planned stage of this work is to see if the technique is also successful for steel and composite plate impact tests.

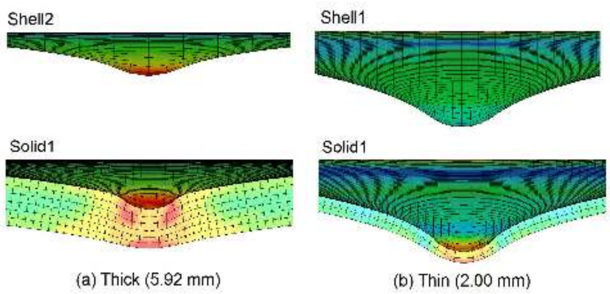

Figure 12: Shape of the deformation. (a) Thick (5.92 mm) circular plates, impact velocity 5.85 m/s. (b) Thin (2.0 mm) circular plates, impact velocity 5.90 m/s.

7 SCALING

Due to the complexity of the impact event confidence in theoretical predictions is not high, especially concerning damage, and so experimental validation of the design process is often necessary. Full-scale testing may not be feasible, and is certainly expensive, and hence scale model testing is attractive.

However, there are scaling issues; it must be certain that there are no unforeseen differences in behaviour that give errors in full-scale prototype predictions obtained from model tests. Such prediction errors are referred to as 'size-' or 'scale-effects'. Considerable work has been carried out in the area of size-effects in composites testing, with a general consensus that these effects are significant, but that there is no one single phenomenon because of the various failure mechanisms involved (Wisnom 1999).

In (Sutherland & Guedes Soares 2007b, 2008) scaling rules for the central, transverse impact of a fully-clamped composite plate with a hemispherical-ended impactor were developed using dimensional analysis techniques and the theory of models. The central transverse displacement was taken as the test variable to be scaled between model and full scale. In order to simplify what is an extremely complex event, the impact behaviour of the composite was assumed to be sufficiently approximated by that of a homogenous and isotropic material.

Summarising the scaling rules developed, when target and impactor head are geometrically scaled by a scaling factor *s*, the same materials are used for model and prototype throughout, and the impact mass is scaled as s^3 and dropped from the same drop height for model and prototype, then we have complete similarity and the central displacement response should also scaled geometrically by *s*.

It was calculated that time is also scaled by *s*, i.e. the impact duration of the prototype would be expected to be *s* times that of the model, the prototype impact force should be s^2 times that in the model, and the prototype absorbed energy will be s^3 times that in the model.

It should be noted that the scaling model used here is simplified. Many aspects, such as the non-homogeneous and non-isotropic nature of the composite materials, the effect of damage, contact stiffness and possible strain-rate effects have not been included in the analysis. If any of these aspects have a significant effect on one or more of the responses then the lack of this effect in this simple analysis could lead to a 'distorted model'. This would produce deviations from the predictions of the analysis, which are often termed 'size-' or 'scale-effects'.

The scaling analysis of the central impact of a fully clamped composite plate described above was verified through an experimental study. A series of tests was carried out at the model scale (i.e. s = 1) and these results compared with equivalent tests at two larger prototype scales (s = 2, and s = 3). Test details are shown in Table 2 where each row corresponds to a series of tests on nominally identical specimens performed at a range of increasing incident velocities.

Although the model was a simplified one, the tests showed that it scaled the impact responses extremely well for the elastic response, as shown in Figures 8 to 11.

However, deviations from the predictions with scale, or 'size effects' were observed:

- The onset of fibre failure was found to be at a relatively lower load and displacement for larger scale specimens.
- For thinner woven roving specimens a higher strain rate also resulted in an earlier fibre failure.
- Relatively more energy was irreversibly absorbed for larger specimens even before fibre damage occurred.
- Membrane stiffening effects were weakest at the largest scale.

These effects indicate that extrapolation from test results to full scale fibre damage behaviour should be carried out with caution.

	s	**No. Plies**	**No. Tests**	**Thickness (mm) Ave. / COV***	**Clamp ∅ (mm)**	**Impact Mass (kg)**	**Head ∅ (mm)**	**Filter (kHz)**
WR	1	5	6	3.06 / 4.1% (6.1%)	100	3.103	10	2
Clamp ∅ /	2	10	6	6.14 / 4.1% (4.8%)	200	24.92	20	1
Thickness = 32	3	15	4	9.44 / 3.0% (4.8%)	300	84.22	30	0.6
WR	1	10	6	6.29 / 2.1% (3.4%)	100	3.103	10	4
Clamp ∅ /	2	20	6	12.12 / 2.0% (3.4%)	200	24.92	20	2
Thickness = 16	3	30	3	18.30 / 2.1% (2.9%)	300	84.22	30	1.3
CSM	1	5	5	4.63 / 2.4% (8.2%)	100	3.103	10	2
Clamp ∅ /	2	10	5	8.84 / 3.2% (5.3%)	200	24.92	20	1
Thickness = 22	3	15	4	14.36 / 4.8% (12.1%)	300	84.22	30	0.75
CSM	1	10	6	8.67 / 5.0% (6.7%)	100	3.103	10	4
Clamp ∅ / Thickness = 11	2	20	6	18.54 / 7.4% (9.9%)	200	24.92	20	2

*Coefficients Of Variation between specimen thickness averages, (values in parenthesis between all thickness measurements).

Table 2: Scaling Specimen and Test Details

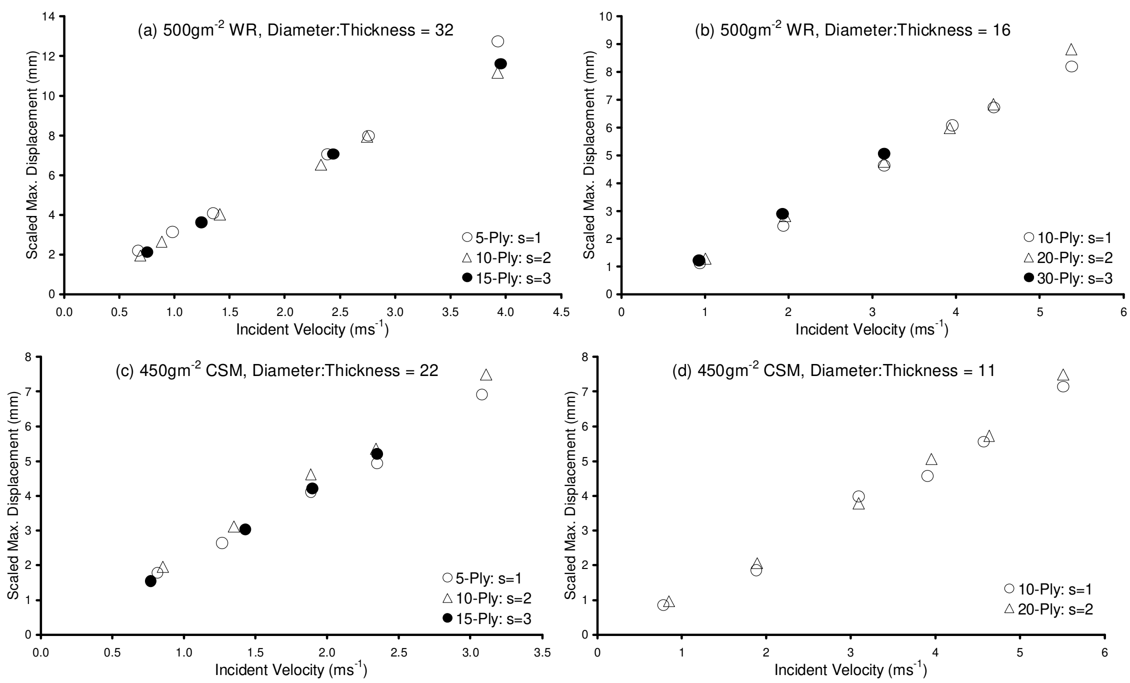

Figure 13: Scaled Maximum Displacement Results (Scale factor *s*)

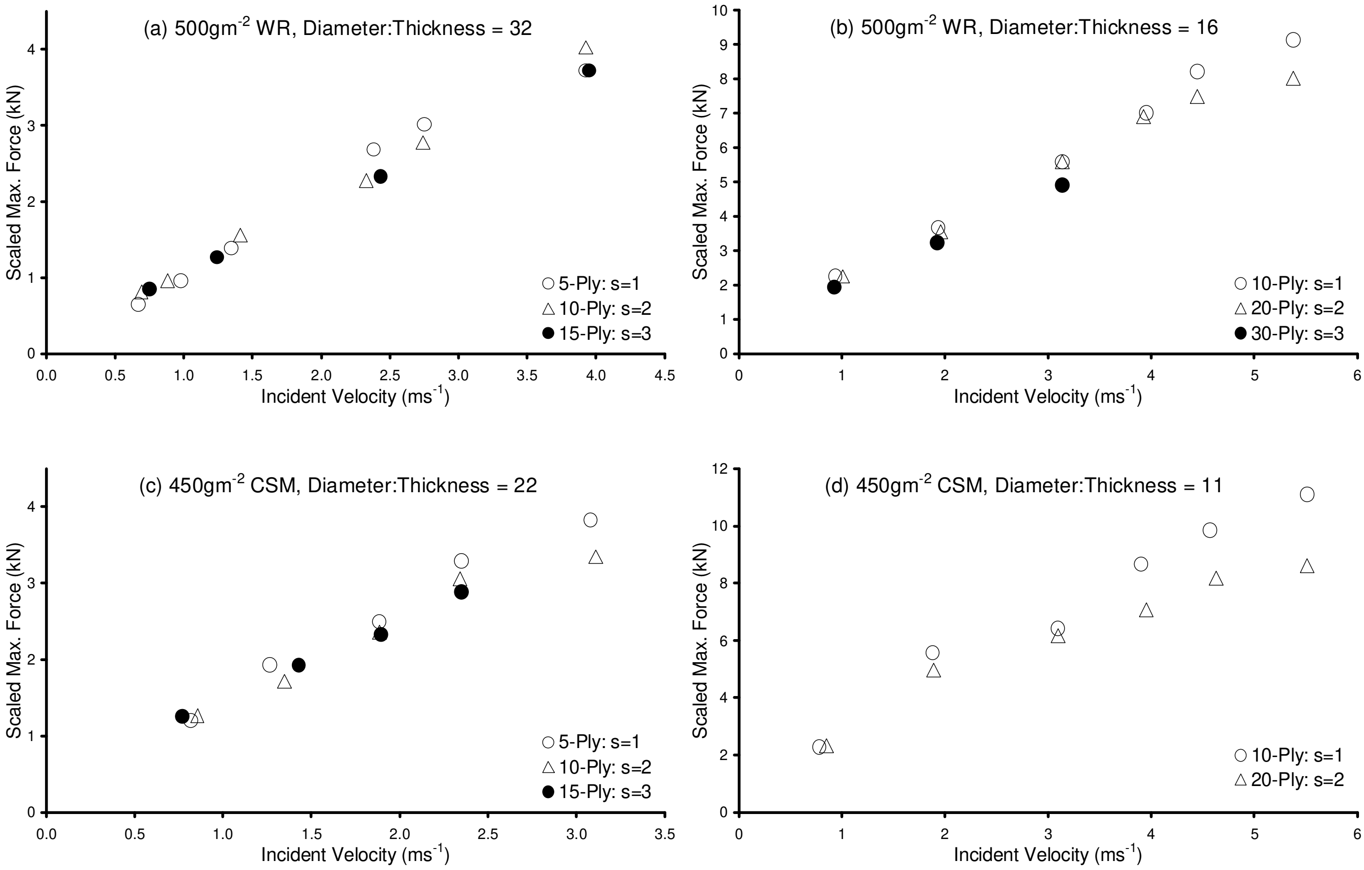

Figure 14: Scaled Maximum Force Results (Scale factor s^2)

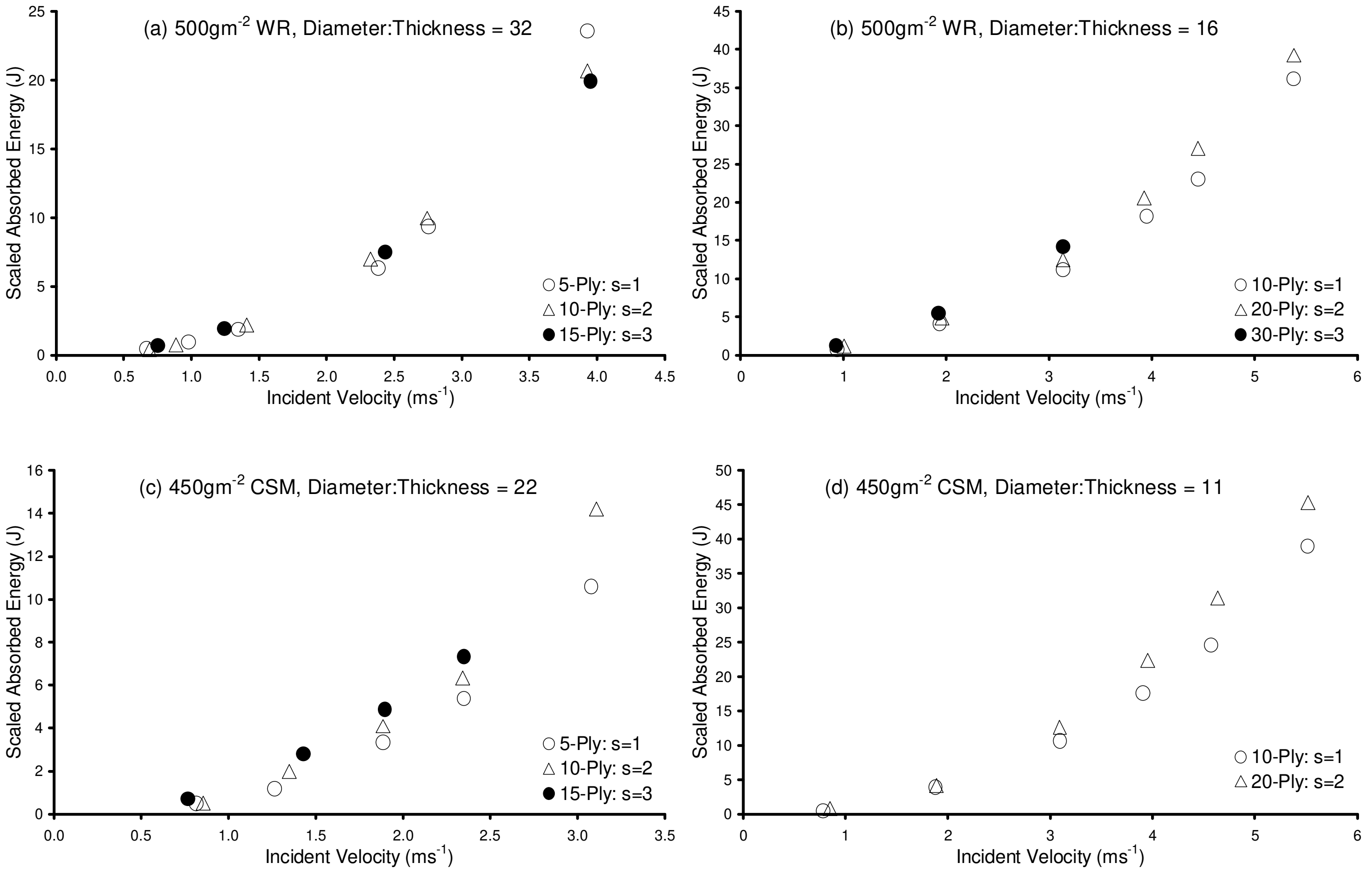

Figure 15: Scaled (Irreversibly) Absorbed Energy Results (Scale factor s^3)

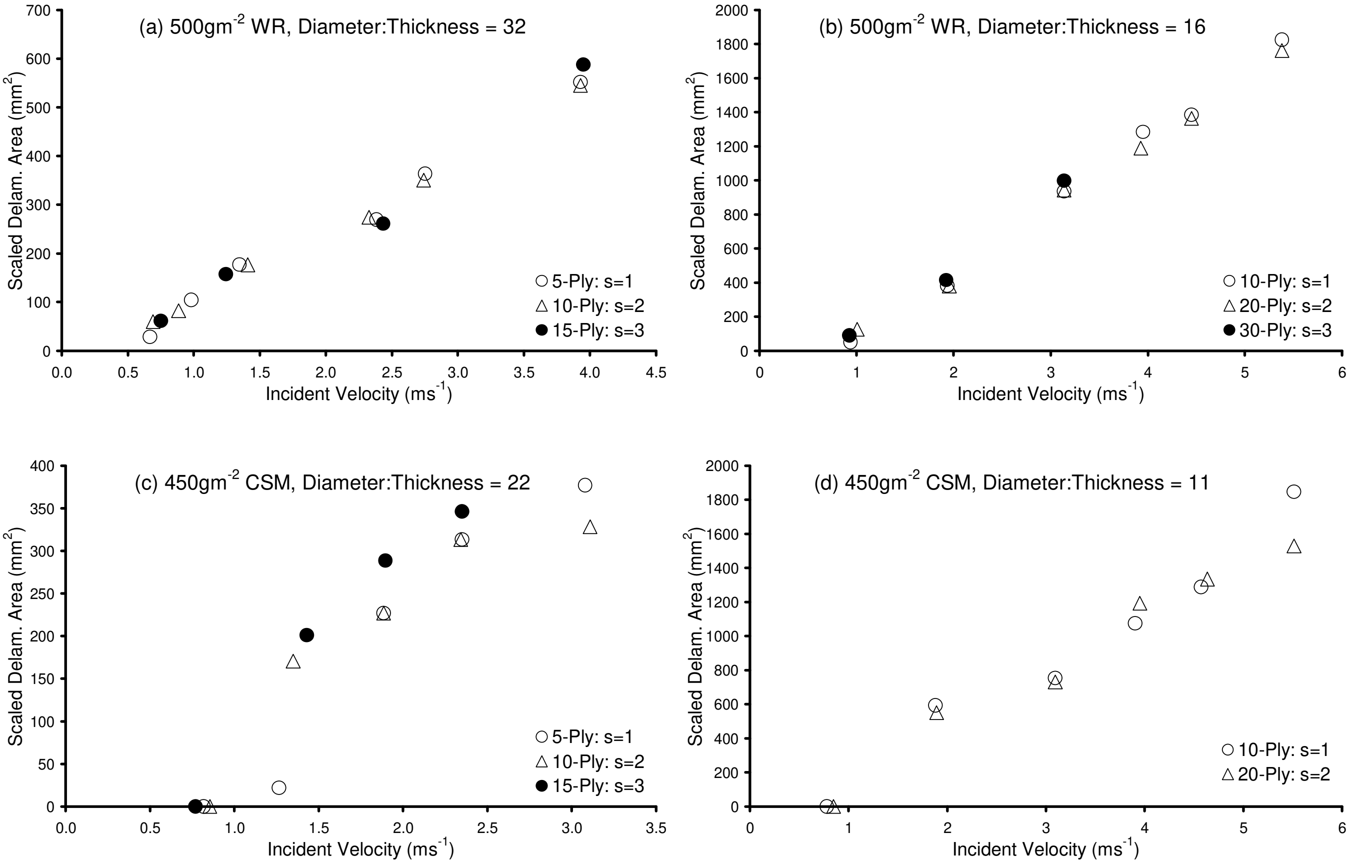

Figure 16: Scaled Delaminated Projected Area Results (Scale factor s^2)

8 QUASI-STATIC TESTS

Impact and identical set-up quasi-static tests on woven roving, chopped-strand mat and cross-ply hand laid up and infused E-glass polyester laminates have been carried out and the results compared to evaluate the validity of using quasi-static data to give the dynamic behaviour Sutherland & Guedes Soares 2011).

Quasi-static tests gave a very good approximation of the onset of delamination and dynamic force-deflection behaviour at low to medium incident energies / displacements for all material systems considered here. However, the onset of fibre failure occurred significantly earlier in the quasi-static tests than was seen in the impact ones, where a greater capacity for energy absorption was observed.

From these results it is inferred that the undamaged and delaminated responses are not strain rate dependant, but that fibre failure mechanisms are, especially for the back face tensile failure exhibited by thinner specimens.

Quasi-static testing avoids the problems associated with the filtering of force signal oscillations, which were often significant but not relevant to the material response. This made it much easier to identify the force at which delamination initiated showed a very strong linear relationship with laminate thickness$^{3/2}$.

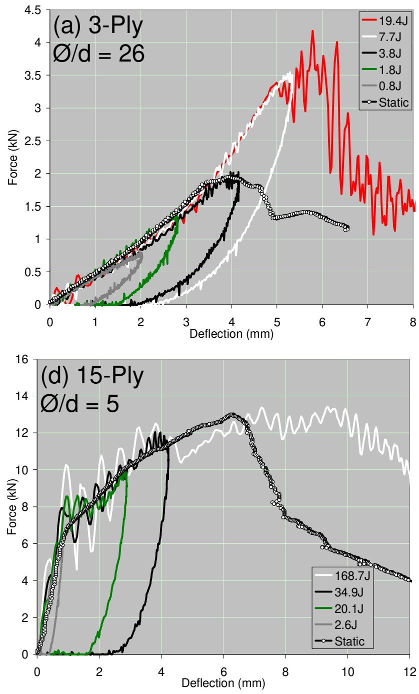

Figure 17: Woven Roving, 50mm Diameter Results

The study shows that more economical quasi-static tests may be used to predict the impact response of the materials studied here if the initial delamination damage is the key design variable. However, if fibre failure and total energy absorption capacity is relevant, then static tests will give only conservative estimates. In all cases, quasi-static testing can provide valuable input to ensure efficient planning of any subsequent dynamic testing.

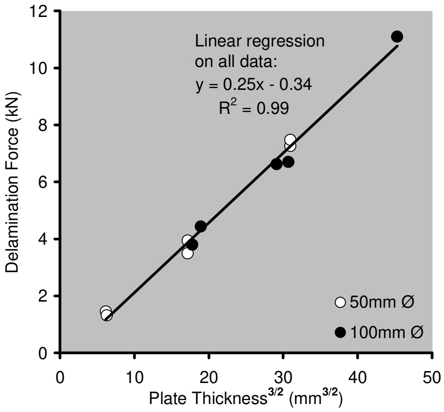

Figure 18: Quasi-Static Critical Delamination Forces

9 CONCLUSIONS

An extensive, mainly experimentally based, study of the impact response of marine composite materials has been carried out at CENTEC. The work has investigated the progression of damage modes with increasing incident energy, the effects of test and material properties, the contact indentation, comparisons between common marine laminates and with steel and marine grade aluminium, scaling effects, and suitability of the use of quasi-static tests to obtain dynamic the response.

This work has provided a wealth of important information on the impact behaviour of the material systems used in the marine industry, and hardly touched upon in the existing literature.

These studies have shown that not only is the impact response of marine composites complex (consisting of the three stages of un-delaminated, delaminated and fibre failure) but that this response is highly dependant on both the exact nature of the impact event and target geometry, as well as the material system considered. Hence, great care must be taken not to blindly assume that results from one specific impact case apply to all cases for a given material, or test set-up.

When a laminate is considered to have ‘good impact properties’, the complex three-stage response mentioned above has almost certainly not been taken into account. It is not enough to say that ‘laminate X’ performs well under impact; further information as to how well it resists delamination, fibre damage, perforation and how the stiffness is affected by damage and so on should also be considered. It is important to realise that a laminate that performs well in one area may well not perform well in another.

This dependence on so many different parameters helps explain why there is so much work in the area, yet the impact response of composites still poses many questions; direct comparisons between studies with even slight differences in material or impact event are difficult, and it is hence very difficult to standardise the impact of composites as one can with real material properties such as, for example, tensile strength.

In fact, the impact behaviour is best thought of as a structural, not a material response, and as such the structural configuration will affect the response and damage modes obtained. Also, the material properties of composites are multiple due to anisotropy, the permutations of fibre, matrix and production method are almost infinite, and in the marine industry production processes are still mostly by hand and less controlled. Further, it is difficult to be sure that laboratory scale and configuration impact testing is representative of full-scale and in-service impact behaviour. A final and significant point is which of the almost infinite number of possible in-service impact events should be considered?

Due to the complex nature of impact on composite materials any mathematical modelling, for example using the finite element analysis, must be correspondingly complex. Hence, any mathematical modelling of impact behaviour should be used with caution; it must be ensured that any changes in failure mode, which have been seen to be induced by small changes in any of many test and material variables, do not compromise the validity or accuracy of the model.

Also, any mathematic model requires accurate material property data as input if it is to have any chance of providing accurate impact behaviour output. Since the material is anisotropic and there are many damage modes in this case there will be a large number of the material properties to be found. This may require a large experimental effort which in itself may require more resources than carrying out experimental impact testing from the beginning. In some cases the experimental methods available to obtain some of these material properties may not even produce particularly accurate values and/or the validity of the properties obtained thus are not universally accepted.

Hence, given the difficulties described above, in a practical sense, what is the best way forward? From the experience gained from the work completed to date, the authors are firmly of the mind that, although numerical modelling techniques may be helpful, an experimental approach is essential. Some recommendations when carrying out such studies are made below.

- It should be decided which target geometry and impact event would be most representative of that likely to be seen in-service. Perhaps a good approach here is to consider a ‘reasonably severe’ case. Thick & thin plate responses should both be considered, with both sharp and blunt impactor geometries.

- Material systems and production methods and conditions should mirror those to be used in service as closely as possible.
- It must be decided which impact behaviours are important; is the main criteria damage resistance, damage tolerance, energy absorption, or others? It is most probable that a good performance in all areas would be ideal, but this would also probably be very difficult if not impossible to achieve.
- Experimental methods should be simple to carry out and analyse, for example quasi-static panel tests have been found to give very good approximations of the un-damaged and delaminated behaviours.
- Maximum force, maximum deflection, and absorbed energy should be measured.
- Any theoretical modelling must be confirmed using experimental tests.

10 ACKNOWLEDGEMENTS

The first author is financed by the Portuguese Foundation of Science and Technology (FCT); for the earlier parts of the work presented here under the contract number SFRH/BPD/20547/2004, and presently under the 'Ciência 2008' programme.

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