Maritime Transportation and Exploitation of Ocean and
Coastal Resources – Guedes Soares, Garbatov & Fonseca (eds)
© 2005 Taylor & Francis Group, London, ISBN 0 415 39036 2

Impact on single-skin marine composites

L.S. Sutherland & C. Guedes Soares
Unit of Marine Technology and Engineering, Technical University of Lisbon
Instituto Superior Técnico, Av. Rovisco Pais, Lisbon, Portugal

ABSTRACT: Studies into the impact on single-skin marine laminates are outlined. Impact damage was seen to occur even at extremely low incident energies. Damage modes were multiple, complex and interacting. The impact response was dependant in a complex manner on a large number of material and impact event variables. Indentations followed Hertzian contact law at low forces, but then contact delamination lead to a linear stiffness relationship. Ongoing work includes studies into scaling, inertial interaction between plate and impacter masses, and quasi-static tests as a cheaper alternative to impact testing.

1 INTRODUCTION

The advantages of the use of laminated composite materials in maritime engineering include high specific mechanical properties, ease of manufacture of complex forms, resistance to rot, corrosion and chemical attack, and low maintenance. Hence, composites are extensively used for fishing, naval and coastguard vessels, and are dominant in the leisure boat industry.

However, these materials are known to be vulnerable to transverse impact damage, arising from such events as collisions, striking floating debris, grounding, docking or dropped objects on board. The resulting damage is often internal and may well remain undetected, and may subsequently grow to a dangerous size with the cyclic loadings normal in the marine environment.

Also, the impact of a composite material is a highly complex dynamic event involving many interacting damage modes, e.g. internal delamination, surface micro-buckling, fibre fracture and matrix degradation (Richardson & Wisheart 1996, Shyr & Pan 2003). These damage modes and paths are dependant in a complex manner on the huge number of material permutations available, e.g. fibre and resin types, quantities, architectures, and interfaces, production method (Cartié & Irving 2002, Caprino & Lopresto 2001, Hirai et al. 1998). The impact event itself is also defined by many variables such as impacter and target geometries, impact velocity and energy (Christoforou 2001, Sutherland & Guedes Soares 2003) and so the 'impact response' of a composite material has proved difficult to standardize.

Hence, a large amount of research into impact on composites has been attempted (in his excellent review Abrate 1998 lists over 500 references), but the complexity of the problem has meant that many aspects remain unclear.

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 most 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 (Collombet et al. 1998, Davies et al. 1997), 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).

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

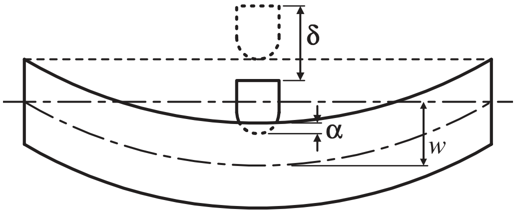

Figure 1. Displacement (δ), Indentation (α) and Deflection (w).

(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.

In this paper the experimentally based work carried out to date, which aimed to investigate all stages of the impact behaviour of single-skin marine composites, is outlined. Initial studies into rectangular plates (Sutherland & Guedes Soares 1999a & b) indicated that the impact response was dependent upon many variables (Section 4), and that the complex damage modes seen required further clarification. Hence, a statistically designed experimental study (Sutherland & Guedes Soares 2003) and further investigations of different laminate thicknesses, resins and reinforcements (Sutherland & Guedes Soares 2005a & b) gave further information on the effects of various parameters (Section 4) and on the damage progression (Section 3).

The study of circular plates enabled the behaviour to be further understood using simpler analyses (Section 3, Sutherland 2005c). This work showed contact indentation to be significant and hence this was also studied (Section 5, Sutherland & Guedes Soares in press). Armed with a greater knowledge of the complex impact behaviour, various common marine laminates were then compared accordingly (Section 4, Sutherland & Guedes Soares in prep.).

The same material production methods were used throughout, and are described in the next section.

2 EXPERIMENTAL DETAILS

The material systems considered used various combinations of Woven Roving (WR) and Chopped-Strand Mat (CSM) E-glass and WR Kevlar reinforcements, with (iso- and ortho-phthalic) polyester and epoxy matrices. However, most of the work presented here considered E-glass/polyester laminates, and unless otherwise stated, the results quoted concern this material combination.

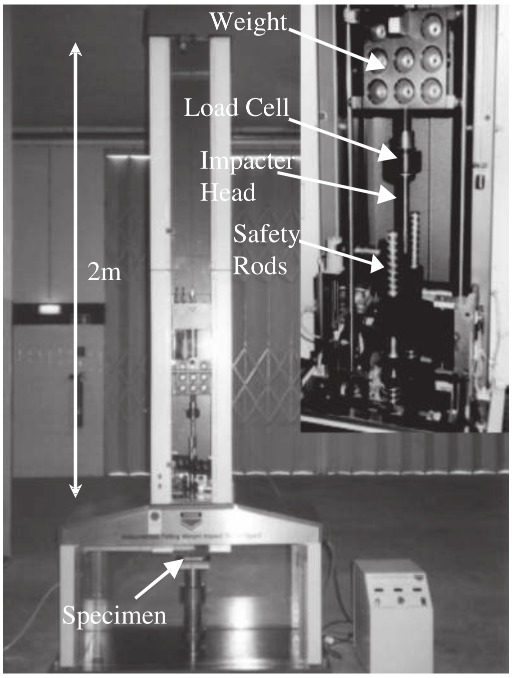

Figure 2. Instrumented falling weight impact machine.

Composite panels of various thicknesses (2 to 20 mm) 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 impacter 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 impacter 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 impacter displacement and velocity and the energy it imparts are calculated from the force-time data by successive numerical integrations. Since the impacter is assumed to remain in contact with the specimen throughout the impact event, the impacter displacement is used to give the displacement and velocity of the top face of the specimen, under the impacter. 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.

The specimens were fully clamped between two thick rectangular 'picture frame' (120 × 75 mm) or annular circular (50 to 300 mm diameters) steel plates. The exact clamping method used was seen to influence the results (Sutherland & Guedes Soares 2003, 2005c). 10, 20 or 30 mm diameter impacter 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 ensures that rebounds did not lead to repeated impacts.

3 TYPICAL BEHAVIOUR

Damage occurred at all but the very lowest incident energies, 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 2005c):

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

However, some differences in damage were seen between 'thin' and 'thick' specimens (the divide 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).

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.

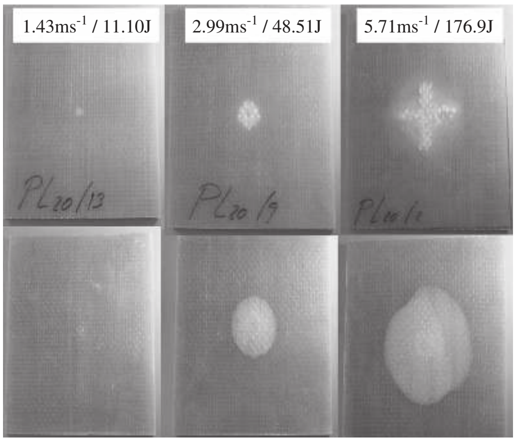

Figure 3. Impacted thin circular clamped laminates.

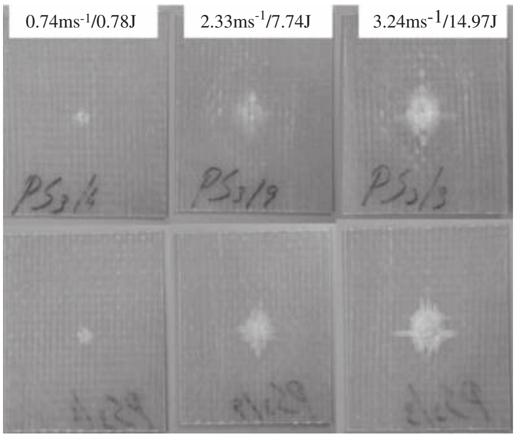

Figure 4. Impacted thick circular clamped laminates.

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 is seen in Figure 5.

A typical plot of absorbed energy with incident energy is presented in Figure 7. 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

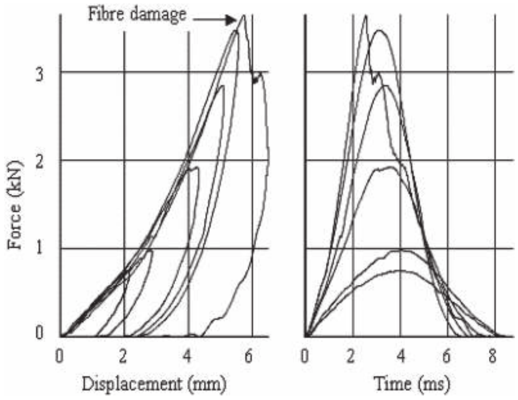

Figure 5. Impact response thin laminate.

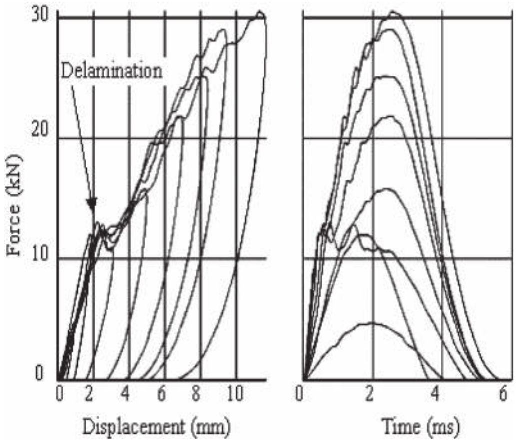

Figure 6. Impact response thick laminate.

as matrix micro-cracking, or due to other mechanisms such as friction or visco-elastic effects is not clear and requires further investigation. The onset of delamination plots is not reflected in this plot. For thicker specimens at higher incident energies, the points rise above the line before a dot indicates the presence of fibre damage corresponding to increased indentation damage.

The corresponding plot of impact duration is shown in Figure 8. For thick specimens the duration remains constant until delamination occurs, resulting in an increase in the length of the impact event. The impact duration remains relatively stable as the delamination grows. A further increase is then seen as first indentation and then fibre damage is seen. Thin specimens show an initial decrease in impact duration as membrane effects increase stiffness, followed by a sharp increase as fibre damage occurs. No effect of delamination on the impact duration is seen for thinner laminates.

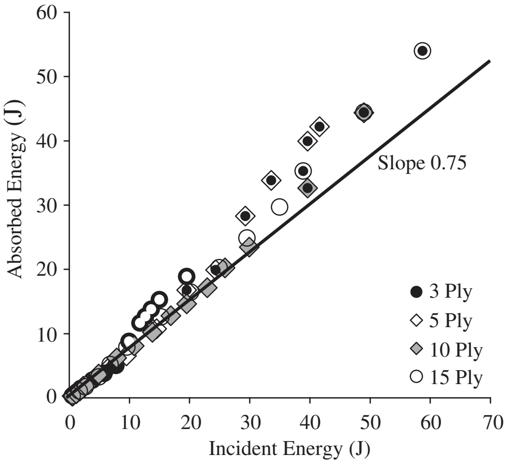

Figure 7. Irreversibly absorbed energy, 50 mm diameter circular specimens. Fibre damage is indicated by a dotted symbol.

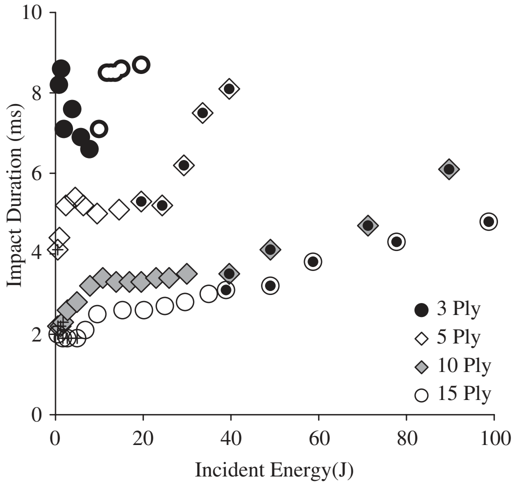

Figure 8. Impact duration, 50 mm diameter circular specimens. fibre damage is indicated by a dotted symbol.

Davies and co-workers (Zhou & Davies 1995, Davies & Zhang 1995, Davies et al. 1993) used a simple mode II fracture analysis to describe the critical load for the unstable onset of a single circular delamination in an isotropic material:

$$P_c = \frac{2\sqrt{2}\pi}{3}\left(\frac{EG_{IIc}}{1-\nu^2}\right)^{1/2} h^{3/2} \tag{1}$$

where E = Young's modulus, G_{IIc} = mode II strain energy release rate, ν = Poisson's ratio, and h = laminate thickness.

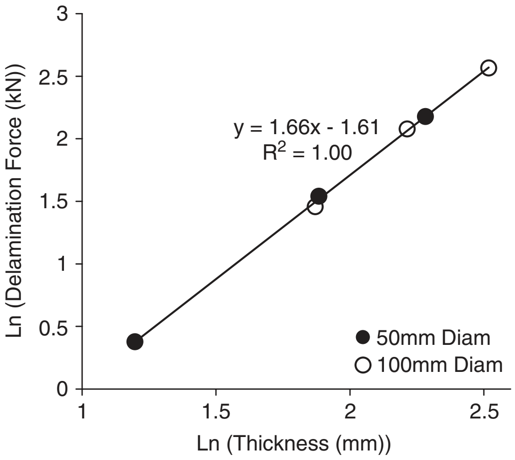

Figure 9. Critical delamination force vs. laminate thickness.

A logarithmic plot of P_c against h for some of the data obtained here for circular WR laminates is shown in Figure 9. The theory fits the data extremely well, as shown by the R^2 value of 1.00, although the slope is slightly higher than the theoretical value of 1.5. Importantly, the theory scales extremely well between the small and large specimens.

4 TEST AND MATERIAL PARAMETER EFFECTS

One of the problems with standardisation of impact response is the dependence of the behaviour on the test set-up. A study using statistical experimental design techniques (Sutherland & Guedes Soares 2003) investigated the effects of clamp geometry (square or circular), clamping surface (steel or with sand paper), and impacter 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 response, but 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 impacter 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 use of iso- or orthophthalic polyester resin was found to be far less important than the amount of crimp in the E-glass WR reinforcement (Sutherland & Guedes Soares 2005a), the latter changed between nominally identical WR supplied by the same supplier, but later found to be from two different manufacturers. The use of epoxy resin gave less internal delamination, but more back-face fibre damage than that of polyester resin (Sutherland & Guedes Soares 2005b).

The impact response of five commonly used lay-ups has been compared experimentally; WR, CSM, alternative 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 1999b, in prep.). Thin and thick 100 mm diameter fully clamped specimens were impacted with a 20 mm diameter hemispherical ended impact head. In order to make meaningful comparisons the panels were designed to be of equal stiffness. At incident energies up to fibre damage the impact responses were very similar for all laminates. Damage trends were again complex, but overall fibre damage was most severe for CSM and CSM/WR laminates. The WR and Kevlar/WR laminates were most resilient to fibre damage, but the Kevlar/WR did not perform better than the WR laminate.

However, great care must be taken not to blindly assume that the results outlined in this section apply in every case. The extensive experimental work carried out to date has led to the conclusion it is best to initially assume that the effects of any parameter may well depend on the exact nature of the impact event as well as the material system considered.

5 INDENTATION

As described in the introduction, locally high forces under the impacter mean that the contact behaviour is of interest. Hence, quasi-static indentation tests have been performed using a servo-hydraulic test machine (Sutherland & Guedes Soares in press). Laminates were fully supported on thick steel blocks and hemispherical

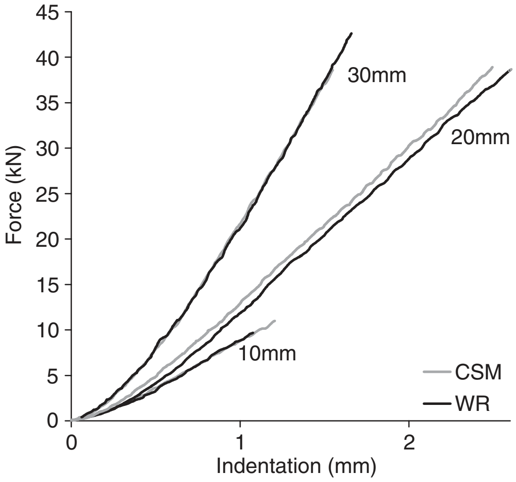

Figure 10. Comparison of WR and CSM contact responses.

ended cylindrical indenters of diameters 10, 20 and 30 mm were pushed onto both chopped strand mat and woven roving reinforced laminates.

Typical results are shown in Figure 10. Despite their significantly lower fibre-volume, chopped strand mat laminates exhibited the same contact stiffness as the woven roving laminates.

The contact force, P, is usually related to the indentation, α, by the Hertz contact law, derived assuming contact between two smooth elastic, homogenous, isotropic solid bodies of revolution (Abrate 2001, Johnson 1985):

$$P = n\alpha^{3/2} \tag{2}$$

For the case of a flat target indented by a hemispherical indenter:

$$n = \frac{4E\sqrt{R_1}}{3} \tag{3}$$

where E = Young's modulus and R_1 = indenter radius. The contact radius, a, is given by:

$$a = \left(\frac{3PR_1}{4E}\right)^{1/3} \tag{4}$$

Despite the fact that laminated composite materials are not homogenous or isotropic, a Hertzian contact law described well the initial response (e.g. Figure 11), but 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. The transition to linear behaviour is thought to be due to observed delamination and was not sensitive to reinforcement type.

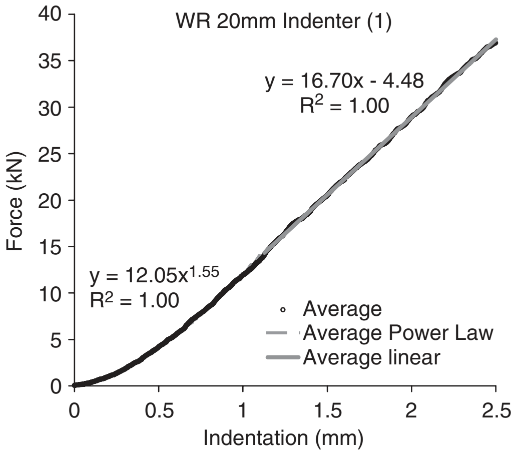

Figure 11. Typical power law and linear response.

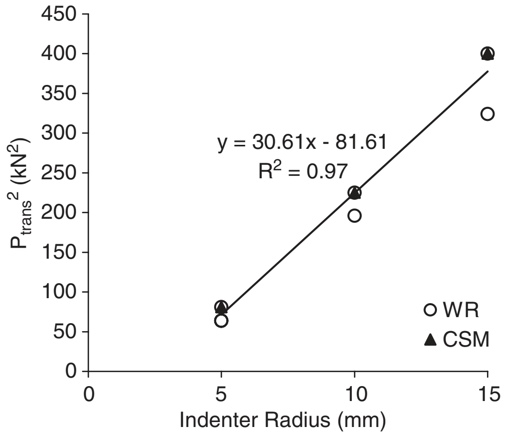

Figure 12. Transition to linear contact response.

Although the local contact stress field leading to delamination is in reality very complex, assuming a greatly simplified shear stress distribution and that the delamination occurs as the interlaminar shear strength (ILSS) is exceeded gives:

$$ILSS = \frac{P_{crit}}{2\pi a h} \tag{5}$$

where, P_{crit} = critical load at which delamination occurs and h = material thickness.

Combining equations 4 and 5 gives:

$$P_{crit}^2 = \left(\frac{6\,ILSS^3\pi^3h^3}{E}\right)R_1 \tag{6}$$

Good correlation of the transition load with indenter radius was seen using this simplified model (Figure 12).

It is thought that this contact induced delamination could be significant in terms of the complex impact damage progression seen in the impact work.

The slope of the linear response increased approximately linearly with indenter radius. The highly complex mechanisms responsible for this behaviour are thought to involve damage progression under a complex stress field and require further investigation.

6 CONCLUSIONS

In this paper previous studies into the impact on single-skin marine laminates have been outlined.

Impact damage occurs even at extremely low incident energies. Damage modes are multiple, complex and interacting, but internal delamination and fibre failure are those most affecting the impact response.

Even when no damage is visible, around 75% of the incident energy is irreversibly absorbed, possibly due to matrix micro-cracking &/or visco-elastic effects.

A simple fracture mechanics model predicts well the onset of internal delamination.

The impact response is dependant in a complex manner on a huge number of material and impact event variables, and hence great care must be made if trying to extrapolate results from one case to another.

Indentation follows Hertzian contact law for low forces, but then contact delamination leads to a linear stiffness relationship.

Preliminary results from current work indicate that dimensional analysis techniques successfully scale impact behaviour but that scaling conflicts are caused by the onset of damage, that inertial interaction between plate and impacter masses are significant, and that replicating the impact event with the quasi-static equivalent may give a cheaper test alternative to impact testing.

ACKNOWLEDGEMENT

This paper has been prepared within the project "MARSTRUCT – Network of Excellence on Marine Structures", (www.mar.ist.utl.pt/marstruct/), which has been funded by the European Union through the Growth programme under contract TNE3-CT-2003-506141.

REFERENCES

Aamlid, O. 1997. Impact properties of different shell structures in relation to rule requirements. Composites and Sandwich Structures; *Proc. 2nd North European Engineering and Science Conference (NESCO II)*, Stockholm, Sweden, 22–23 October 1997.

Abrate, S. 1998. *Impact on Composite Structures*. Cambridge UK: Cambridge University Press.

Abrate, S. 2001. Modelling of impacts on composite structures. Composite Structures 51: 129–138.

Caprino, G. & Lopresto, V. 2001. On the penetration energy for fibre-reinforced plastics under low-velocity impact conditions. *Composite Science and Technology* 61: 65–73.

Cartié, D.D.R. & Irving, P.E. 2002. Effect of resin and fibre properties on impact and compression after impact performance of CFRP. *Composites Part A* 33: 483–493.

Chen, J.K. & Sun, C.T. 1985. Dynamic large deflection response of composite laminate subject to impact. *Composite Structures* 4(1): 59–73.

Christoforou, A.P. 2001. Impact dynamics and damage in composite structures. *Composite Structures* 52: 181–188.

Collombet, F., Pecault, S., Davies, P., Choqueuse, D., Lataillade, J.L. & Marques, A.T. 1998. Contribution of the response surface methodology to the study of low velocity impact on sandwich structures. In A. Vautrin (ed.), Mechanics of Sandwich Structures: 255–262. *EUROMECH 360 - Mechanics of Sandwich Structures, Saint-Etienne, France, 13–15 May 1997*. Dordrecht: Kluwer Academic Publishers.

Davies, G.A.O. & Zhang, X. 1995. Impact damage prediction in carbon composite structures. *Int J Impact Eng* 16(1): 149–170.

Davies, G.A.O., Hitchings, D. & Zhou, G. 1993. Impact damage and residual strengths of woven fabric glass/polyester laminates. *Composites Part A* 27A: 1147–1156.

Davies, P., Baizeau, R., Wahab, A., Pecault, S., Collombet, F. & Lataillade, J.L. 1998. Determination of material properties for structural sandwich calculations: from creep to impact loading. In A. Vautrin (ed.), Mechanics of Sandwich Structures: 327–337. *EUROMECH 360 - Mechanics of Sandwich Structures, Saint-Etienne, France, 13–15 May 1997*. Dordrecht: Kluwer Academic Publishers.

Hildebrand, Martin. 1996. *A comparison of FRP-sandwich penetrating impact test methods.* VTT Publications 281, Espoo, Technical research Centre of Finland.

Hildebrand, Martin. 1997. *Local impact strength of various boat-building materials.* VTT Publications 317, Espoo, Technical research Centre of Finland.

Hirai, Y., Hamada, H. & Kim, J.K. 1998. Impact response of woven glass-fabric composites – I. Effect of fibre surface treatment. *Composite Science & Technology* 58: 91–104.

Johnson, K.L. 1985. Contact mechanics. Cambridge, UK: Cambridge University Press.

Mouritz, A.P., Gellert, E., Burchill, P. & Challis, K. 2001. Review of advanced composite structures for naval ships and submarines. *Composite Structures* 53: 21–41.

Naik, N.K., Chandra Sekher, Y. & Sailendra, Meduri. 2000. Damage in woven-fabric composites subjected to low-velocity impact. *Composites Science and Technology* 60: 731–744.

Richardson, M.O.W. & Wisheart, M.J. 1996. Review of low-velocity impact properties of composite materials. *Composites Part A* 27A: 1123–1131.

Shivakumar, K.N., Elber, W. & Illg, W. 1985. Prediction of impact force and duration due to low-velocity impact on circular composite laminates. *J. Appl. Mech.* 52: 674–680.

Shyr, T.W. & Pan, Y.H. 2003. Impact resistance and damage characteristics of composite laminates. *Composite Structures* 62: 193–203.

Sutherland, L.S. & Guedes Soares, C. 2005b. Effect of laminate thickness and of matrix resin on the impact of low fibre-volume, woven roving E-glass composites", *Composites Science and Technology* 64: 1691–1700.

Sutherland, L.S. & Guedes Soares, C. 1999a. Impact tests on woven roving E-glass/polyester laminates. *Composites Science and Technology* 59: 1553–1567.

Sutherland, L.S. & Guedes Soares, C. 1999b. Effects of laminate thickness and reinforcement type on the impact behaviour of E-glass/polyester laminates. *Composites Science and Technology* 59: 2243–2260.

Sutherland, L.S. & Guedes Soares, C. 2003. The effects of test parameters on the impact response of glass reinforced plastic using an experimental design approach. *Composites Science & Technology* 63: 1–18.

Sutherland, L.S. & Guedes Soares, C. 2005a. Impact of low fibre-volume, glass/polyester rectangular plates. *Composites Structures* 68:13–22.

Sutherland, L.S. & Guedes Soares, C. 2005c. Impact characterisation of low fibre-volume glass reinforced polyester circular laminated plates. *International Journal of Impact Engineering* 31: 1–23.

Sutherland, L.S. & Guedes Soares, C. In prep. Impact behaviour of typical marine composite laminates.

Sutherland, L.S. & Guedes Soares, C. In Press. Contact indentation of marine composites. *Composites Structures*.

Tan, T.M. & Sun, C.T. 1985. Use of statical indentation laws in the impact analysis of laminated composite plates. *J. Applied Mechanics* 52: 6–12.

Wiese, M., Echtermeyer, A.T. & Hayman, B. 1998. Evaluation of oblique impact damage on sandwich panels with PVC and balsa core materials. *Fourth International Conference on Sandwich Construction,* Stockholm, Sweden.

Zhou, G. & Davies, G.A.O. 1995. Impact response of thick glass fibre reinforced polyester laminates. *Int J Impact Eng* 16(3): 357–374.