The use of quasi-static testing to obtain the low-velocity impact damage resistance of marine GRP laminates

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Abstract

The use of more economical quasi-static testing to predict the dynamic impact behaviour of marine GRP composites has been evaluated by comparing equivalent impact and quasi-static test results. Static tests predicted well the initial impact behaviour and onset of delamination damage, which is likely to be the key impact resistance design variable. However, only very conservative estimates of the final fibre failure and total energy absorption capacity were achieved, except for the thickest specimens where fibre damage occurred at similar loads for both static and impact tests. Quasi-static testing avoided the problems associated with oscillations in the force signal, and delamination force showed a very strong linear relationship with laminate thickness$^{3/2}$ as predicted by two simplified models. It was inferred that the undamaged and delaminated responses are not strain rate dependant, but that the fibre failure mechanisms are.

Keywords

B. Impact behaviour, D. Mechanical testing, A. Glass fibres, B. Delamination

1. Introduction

The use of reinforced plastic composite materials for marine applications promises many advantages over the use of more ‘traditional’ materials (e.g. steel, aluminium, wood) such as high specific material properties, resistance to corrosion and rot, and ease of forming complex shapes. Hence, laminated fibre-reinforced composite materials are widely used in the marine industry; composites are by far the dominant material for pleasure boat and racing yacht construction, are extensively used in the construction of fast ferries, naval and coastguard patrol craft, fishing and work boats, and are fast being adopted for use in the offshore oil and gas industry.

However, one of the main restrictions to the use of laminated composite materials is that they are known to be very susceptible to impact damage especially that due to out of plane impact events. In a marine environment, common impact events include collisions with floating debris, other craft, docks, grounding, and during production (e.g. ‘tool drops’) all of which are low-velocity impacts. In fact, where the weight savings from using composite materials would be most beneficial, i.e. for high speed craft, the question of impact damage is most relevant. However, impact is also a problem for slower vessels, e.g. for fishing boats where impacts between the fishing equipment and the structure are probable.

The impact of an object on a composite material is a complex and dynamic event; global deflections are usually large, and membrane effects or shear deflections are usually significant, e.g. [1]; concentrated local forces at the impact point give non-linear contact behaviour, e.g. [2]; damage modes are numerous (including matrix micro-cracking, internal delamination, ply shear-out and fibre fracture [3]) and interacting [4] and damage may occur both due to global deflections and due to local contact forces, e.g. [5].

Further, the various response and damage modes will almost certainly vary (both quantitatively and qualitatively) with changes in the type and nature of both the specific composite material considered (e.g. reinforcement and matrix materials, fibre architecture and volume fraction, etc.) and of the nature of the specific impact event considered (e.g. both target and impactor form and dimensions, target clamping conditions, etc.), e.g. [4,6,7].

Hence there is a great deal of existing work in the area; for example the reviews of Richardson and Wisheart [5], Cantwell and Morton [6], Bibo and Hogg [8], Abrate [9], Reid and Zhou [10], Elder et al. [11], Resnyansky [12,13], and Bartus and Vaidya [14] between them provide well over 1500 references.

By far the great majority of this literature available concerns high fibre volume fraction, carbon composites destined for the aerospace industry. Far fewer studies have concerned the lower fibre-fraction glass composites still ubiquitous in the marine industry, where materials are far more variable and not at all standardised, and where the resources available for investigating material behaviour are generally much scarcer. Also, the impact events likely to be seen in the marine environment are not the same as those to be expected for aircraft or space vehicles. Even fewer publications are available from these studies since the work was often of a sensitive military or commercial nature.

The authors have published a series of studies investigating various aspects of low energy impact on monolithic GRP marine laminates [2,4,15–21]. The classification society DNV have performed a series of test programmes on oblique impact with various single-skin and sandwich lay-ups relevant to high speed craft hulls [22,23]. Hildebrand compared the impact strength of various boat-building materials [24] and test methods, particularly the influence of impactor shape [7]. Davies et al. [25–28] investigated both solid object and water 'slamming' impacts on monolithic and sandwich marine composites. Experimental design methods were used to investigate the effects of span, velocity and mass, and a scaling study successfully scaled some impact results, but larger scale tests were thought to be needed. Johnson et al. [29] numerically modelled the impact damage suffered by vacuum assisted resin transfer moulding (VARTM) produced woven roving single-skin marine laminates. Atas and Sevim [30] present an experimental investigation on impact response of sandwich composite panels with stitched E-glass/epoxy skins and PVC foam and balsa wood cores, as commonly used in the marine industry.

Since there is very little literature concerning impact on marine composites, and since what is available is almost certainly will not consider the exact material/impact event combination in question, it will almost always be necessary to obtain data for the specific case at hand due to a lack of available design data. Two main methods to achieve this are through numerical modelling (usually finite element analyses) and experimentation.

Finite element analysis is a useful tool, and has now even been used to successfully predict damage, e.g. [29], but this type of numerical modelling is not as economic as might be expected since a large amount of experimental effort is required to obtain the many material property inputs required and accurate values of these material properties may be very difficult to obtain due to physical constraints and/or inherent errors in the testing methods available. This is especially relevant in the marine industry where materials are far more variable, and not at all standardised, and so materials property testing must be carried out in each specific case. Further experimental effort is also required to ‘calibrate’ the FE model and to verify its results. In any case, the expertise and resources required to both develop the model and analyse its results will almost certainly be unavailable or prohibitively expensive in the marine industry.

Hence, impact experimentation emerges as a more direct solution, but also has its own restrictions; expensive impact equipment to record the dynamic response is required, filtering of the data due to oscillations in the signals may be problematic, and analysis of the results is complex. Also, since full scale impact testing is usually prohibitively expensive, the problems of scaling up laboratory scale component or coupon behaviour to that of the in-service structure must be addressed, and although some progress has been made in this area little work has addressed this issue [15,31].

A very attractive option to reduce experimental costs would be to obtain the impact behaviour through the use of much simpler, cheaper and more widely available quasi-static testing. However, since the strain-rate dependency of composite material properties is still an unresolved question, and since there are varied mechanisms controlling the impact response (which probably explains why no consensus on impact strain rate effects has been reached), it must be confirmed if and exactly under which circumstances quasi-static testing will give a good representation of impact results. This approach has been applied successfully to aerospace type graphite/epoxy pre-preg composite monolithic, sandwich plates and shells by Lagase and co-workers [32,33]. Static indentation tests and impact tests were generally seen to give similar force/displacement and damage behaviours, although this was not true in all cases, for example differing static and impact force-deflection responses for the $[\pm 45_2/0_2]_s$ laminates studied. Alderson and Evans [34] found that the first failure modes of E-glass/Epoxy filament wound pipes were the same for static and impact tests, but that subsequent damage modes depended on both the type of test (static or impact) and the test set-up. Conversely, Aymerich et al. [35] concluded that for graphite/PEEK laminates the use of static tests would not give the same responses as impact tests, and that it would be hazardous to try to simulate dynamic events with equivalent static tests. However, this approach has not been validated for the types of E-glass/polyester laminates ubiquitous in the marine industry.

Hence, the aim here is to explore the use quasi-static testing to obtain valuable information about the impact response of marine composites. Results from quasi-static and dynamic impact tests using exactly the same experimental set-up are compared for a range of composite materials commonly used in the marine industry in order to evaluate which information may be reliably obtained through the far more accessible quasi-static testing for the range of typical marine laminates considered here. Since the study is aimed at composites for shipbuilding use, the low-velocity impact on Glass Reinforced Plastic (GRP) laminates is considered here.

2. Experimental details

Three series of tests, corresponding to three different E-glass reinforced polyester laminates (those most commonly found in the marine industry) were completed; Woven Roving (‘WR’), Chopped Strand Mat (‘CSM’) and Cross-Ply (‘CP’). The WR and CSM specimens were fabricated using hand lay-up, but the cross-ply specimens were also produced using vacuum resin infusion to allow the investigation of the effect of production method. All laminates were symmetrical about the mid-thickness and were left for at least 2 months before testing to ensure an acceptable and comparable level of cure.

Plate material and geometry details are given in Table 1 for each series. Specimens were cut from the laminated panels using a diamond-surrounded circular saw, and the average of four thickness measurements at different points on each specimen recorded prior to testing.

Material	**Production method**	V_f	**Plate/indentor diameter (mm)**	**Number of plies**	**Average thickness (mm)**
WR	Hand lay up	0.35	50/10	3, 5, 10, 15	1.9, 3.3, 6.6, 9.8
500 gm^{-2}			100/20	5, 10, 15, 20	3.3, 6.5, 9.2, 12.4
CSM 450 gm^{-2}	Hand lay up	0.20	100/20	5, 10	5.4, 9.4
CP	Hand lay up	0.40	100/20	5, 10	3.1, 6.1
600 gm^{-2}	Infusion	0.55	100/20	5, 10	2.4, 4.6

Table 1. Specimen materials and geometries.

Impact tests were made using a Rosand IFW5 instrumented falling weight machine. A small, light hemispherical ended cylindrical impactor was 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 gave the variation of impact force with time. An optical gate gave the incident velocity, and hence the impactor displacement was calculated from the force-time data by successive numerical integrations. Since the impactor was assumed to remain in contact with the specimen throughout the impact event, the impactor displacement was used to give the displacement of the top face of the specimen, under the impactor. Specimens for both static and impact tests were fully clamped between thick steel rectangular plates with annular cut-outs (to give a circular plate target geometry) and sand-paper lined faces (Fig. 1) using four M10 bolts passing through both support plates and specimens. In all cases these bolts were tightened as far as possible by hand. This ensured a sufficient and very consistent degree of clamping (as shown by the very good repeatability of both the impact and static tests, as illustrated in Figs. 2–6). Previous experience had already shown that, due to the rough and very variable un-moulded surface of these laminates, the use of a torque wrench introduced a less consistent degree of clamping. For each material system considered, the impact responses at various increasing incident energies up to perforation failure (where possible) were obtained by separate impact tests carried out on nominally identical virgin (i.e. untested) specimens cut from the same laminated panel.

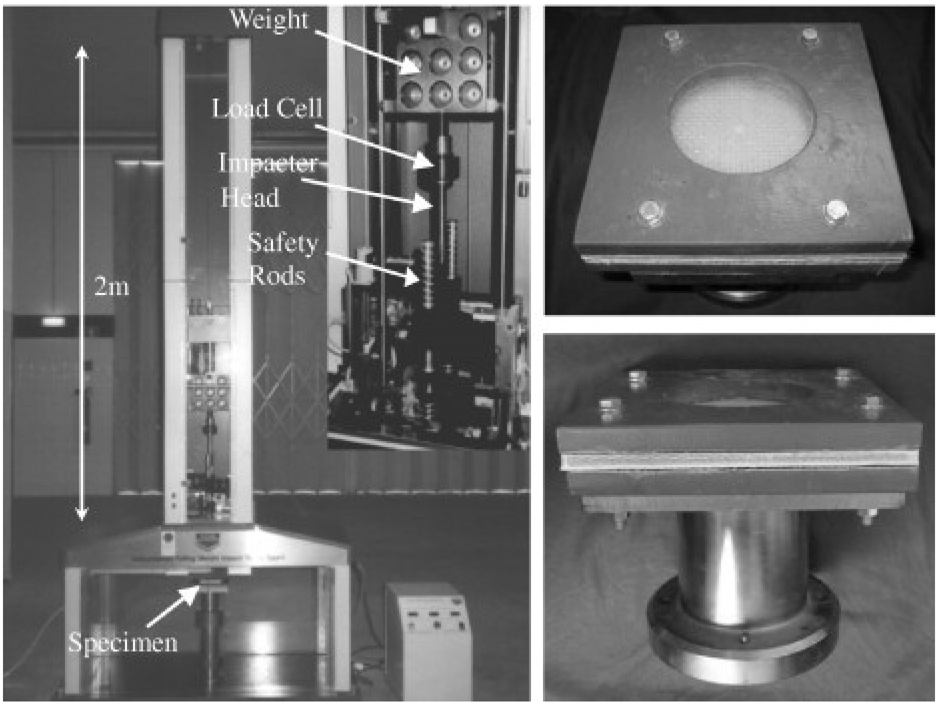

Fig. 1. Impact machine and specimen clamping.

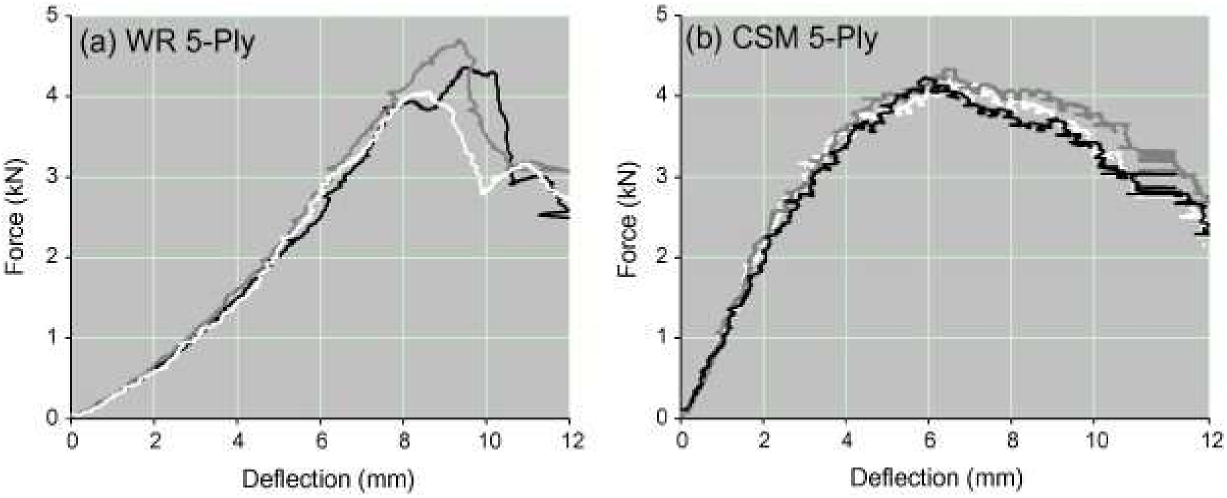

Fig. 2. Example quasi-static results.

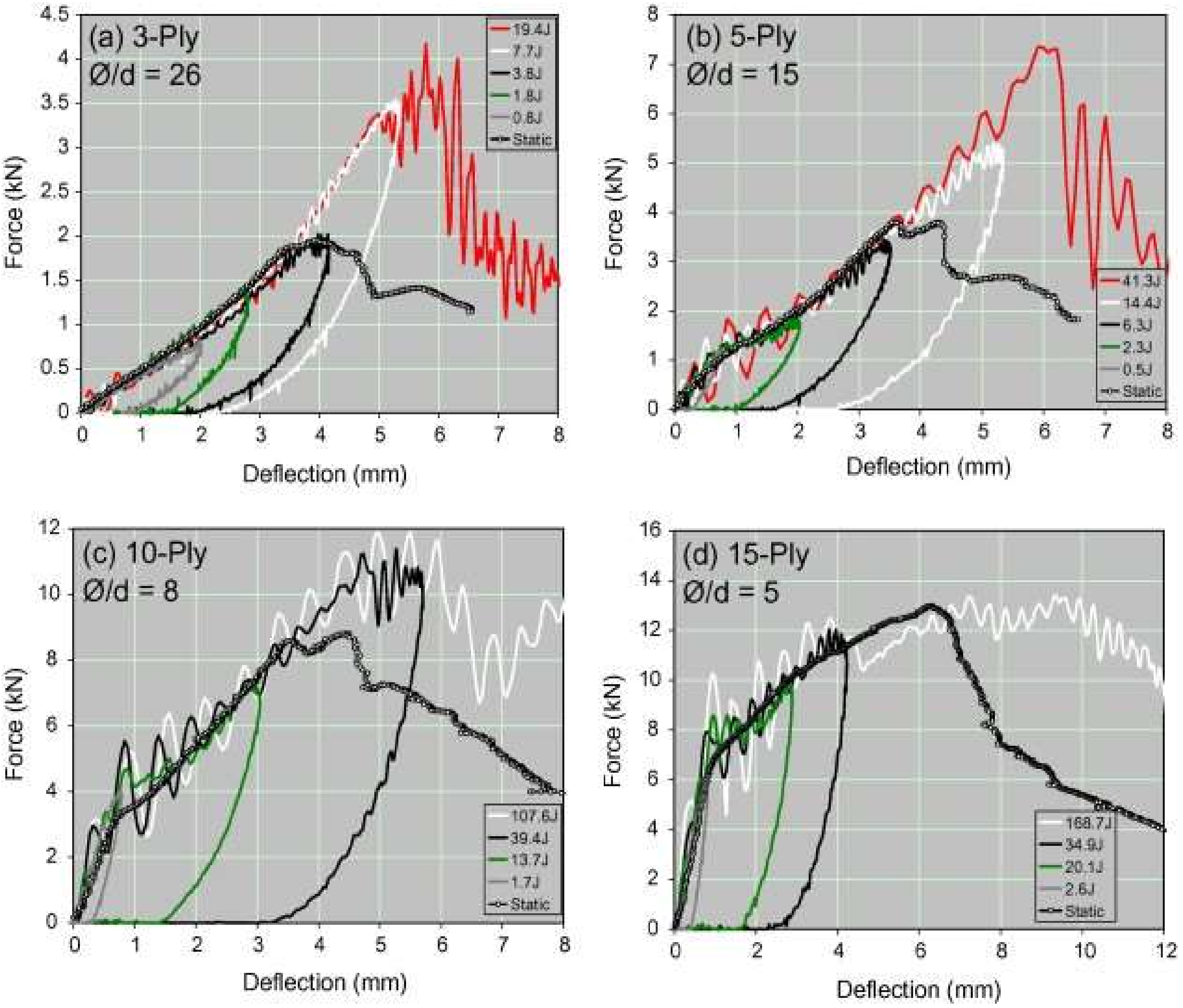

Fig. 3. Woven roving, 50 mm diameter results.

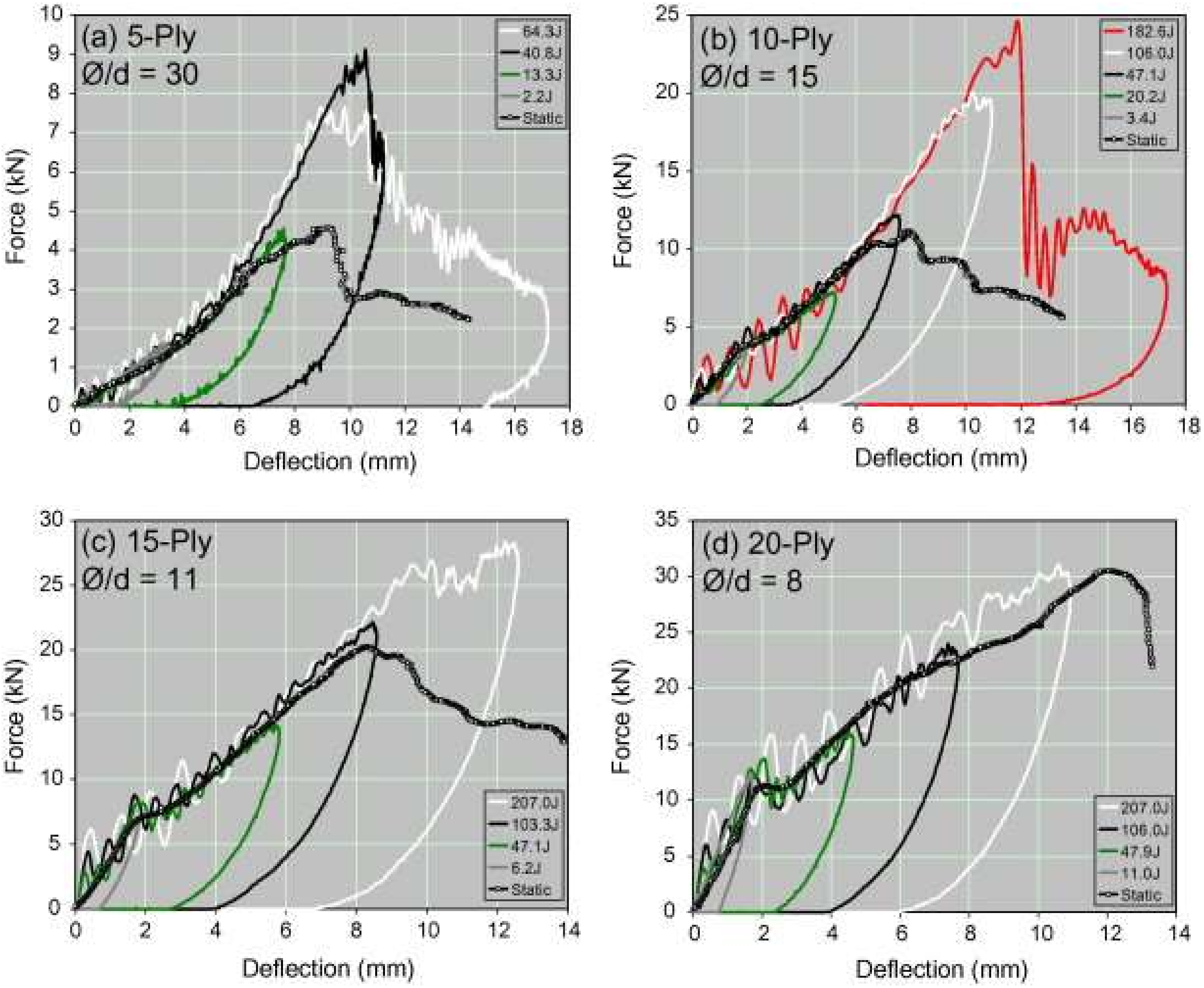

Fig. 4. Woven roving, 100 mm diameter results.

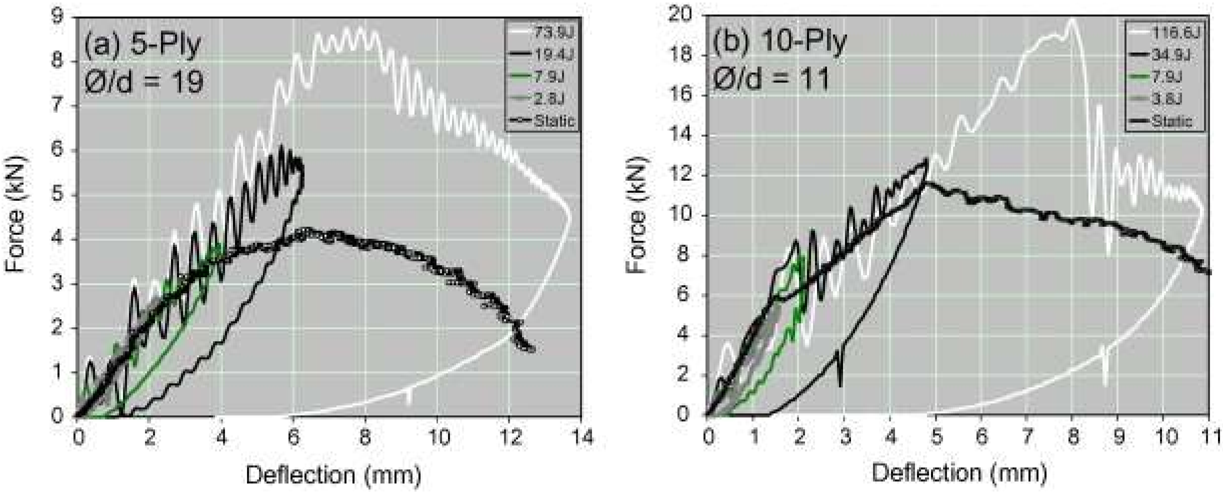

Fig. 5. Chopped strand mat, 100 mm diameter results.

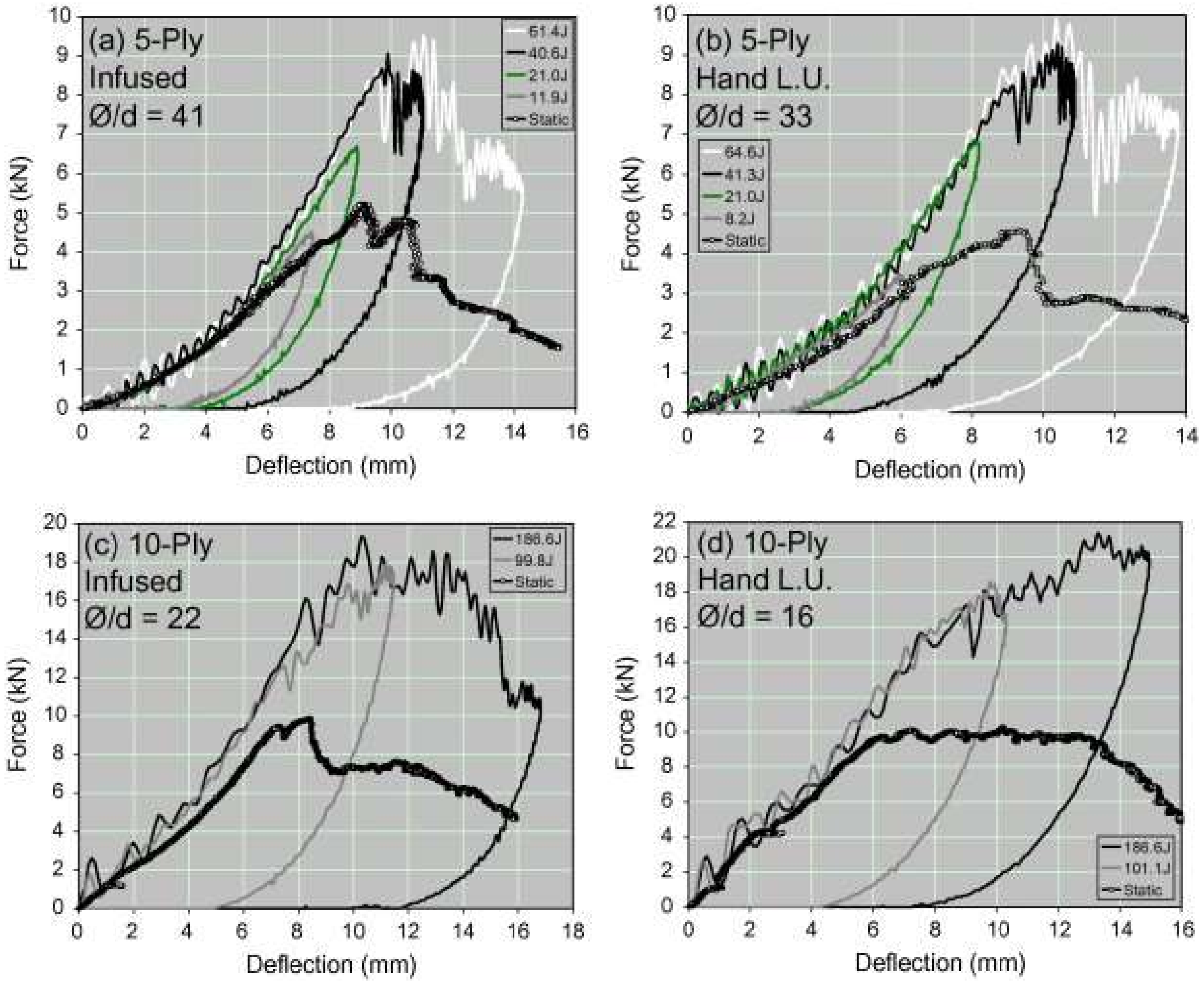

Fig. 6. Cross-ply, 100 mm diameter results.

Quasi-static tests were then carried out on an instrumented servo-hydraulic test machine at a constant rate of displacement until perforation occurred. Exact replication of the impact test set-up was ensured through using the same clamping supports as used in the impact tests, and by using the same impact ‘tup’ or ‘nose’ to apply the quasi-static load.

3. Results

Since for impact tests a higher incident energy corresponds to a higher displacement, and for static tests ‘incident energy’ has no meaning, the displacement will be used in the following discussions as a measure to enable valid comparisons to be made between the dynamic and quasi-static results.

The same development of damage modes with increasing impact energy (and hence maximum displacement) as reported in previous work [16] were seen here; Circular internal delamination occurred at a very low incident energy for all tests, which grew with increasing energy until at higher energies fibre damage occurred. The thinner specimens tended to give ‘back-face fibre damage’ as large global deflections gave high strains, the thicker specimens tended to first give permanent indent damage on the ‘front’ or impacted face that then developed into ‘front-face fibre damage’. In both cases, once the initial damage became more severe with increasing energy, fibre damage could occur on the other face, leading to penetration, and finally perforation. ‘Fibre failure’ of the WR laminates consisted of breakage of the continuous fibres, whereas for CSM laminates ‘pull-out’ of the short discontinuous fibres occurred.

The same progression of damage was seen in the quasi-static tests as the displacement of the indentor increased. Typical quasi-static results (filtered to remove electrical noise using a moving average filter) are shown in Fig. 2. Three tests are shown in each plot, and the high repeatability up to perforation is clear, although there is some variation corresponding to fibre failure, penetration and perforation of the woven roving specimens.

In Figs. 3–6 the impact results are compared with those of the quasi-static tests for the various material systems, and plate diameters and thicknesses studied. The quasi-static tests were very repeatable, and hence in order keep the plots legible only one quasi-static result is shown in each graph. As discussed in the next section, the filtering of the impact force signal may lead to errors and misinterpretation of the data and hence the impact data presented here is unfiltered.

For both the dynamic and quasi-static cases the thicker plates showed the typical bi-linear force–displacement response with a sudden reduction in stiffness as delamination occurred, and at higher displacements (corresponding to higher impact energies in the dynamic case) a drop in force to fibre damage was evident (e.g. Fig. 3c).

The thinner plates exhibited the increasing stiffness associated with membrane effects, again followed by load drops due to fibre failure, but although observed in the tested specimens the delamination incurred did not lead to any discernable corresponding drop in stiffness in the force displacement response for dynamic or quasi-static tests (e.g. Fig. 4a).

4. Discussion

Since the aim here is to verify the validity of using cheap and simple quasi-static tests to give information on the damage resistance of marine composites, it will be helpful to first give a brief description of the damage incurred by these types of laminate.

The authors’ previous work [e.g. 16,18] has shown that for these low fibre volume E-glass/polyester laminates there are generally three main ‘regimes’ of impact behaviour, which have also been observed here, as described in the previous section;

(i) ‘Un-delaminated’
(ii) ‘Delaminated’
(iii) ‘Fibre Damage’

Further, the impact behaviour can be characterised into two main categories, namely ‘thick’ and ‘thin’ behaviour. For these materials, and the impact set-up considered, a diameter to thickness ($Ø/d$) ratio of around 15 can be used as a limit between the two types of behaviour [36], but since the change in behaviour is gradual and intermediate type behaviour is seen, this value should be used as a guide only.

The difference between the ‘thin’ and ‘thick’ impact responses is best described in terms of the force–displacement behaviour. ‘Thick’ specimens exhibit bi-linear stiffness behaviour; an initial higher linear stiffness is seen followed by a sudden reduction in stiffness as delamination suddenly occurs. This approximately linear reduced stiffness behaviour continues until various sudden load drops are seen as fibre failure leads to penetration and perforation. For ‘thin’ specimens, due to the larger displacements, membrane effects give progressively increasing stiffness behaviour until similar load drops due to fibre failure are dominant. Although delamination is also suffered by ‘thin’ laminates, in this case this (generally less severe) damage shows no discernible effect on the force–displacement behaviour.

Hence, in terms of impact damage resistance there are two main damage mechanisms of interest; namely ‘delamination’ and ‘fibre failure’. The former is more important for higher diameter to thickness ratios, and the exact mechanisms responsible for the latter will depend on the diameter to thickness ratio.

Fibre failure may be thought of as an ‘ultimate’ strength, and since this leads to perforation is perhaps the most obvious concern in a marine context where, for example, a breech in the hull may well lead to loss of the vessel through sinking. However, it should not be forgotten that delamination is equally important since this can also lead to failure of the structure, most probably due to compression instability, and also since this damage mode is suffered at even seemingly innocuous impacts of extremely low incident energy.

Failure of the structure due to delamination may occur either immediately if the delamination is large enough, or delamination may reduce the load bearing capability such that the reduced magnitude of the peak wave load required to cause structural failure is now statistically likely to occur much earlier in the structures life than envisaged during the design process. Also, due to the ubiquitous wave loadings present in the marine environment, cyclic loadings may cause the delamination to grow, leading to a catastrophic failure in the future. These delayed structural failures due to impact delamination are especially sinister since such delamination will remain hidden in-service, and the resultant future failure may well be completely unexpected, months or even years after the initial impact event occurred.

The use of quasi-static identification of the impact resistance of the marine laminates studied here in terms of these two main damage modes will now be discussed through a comparison of the quasi-static and dynamic impact test results of the previous section, for each of the material systems considered in turn. Finally comments will be made concerning the advantages of quasi-static testing in avoiding the unwanted force signal oscillations associated with dynamic impact testing, and the modelling of the onset of delamination discussed in this light.

Figs. 3 and 4 show that for the WR laminates the quasi-static tests gave a very accurate prediction of the dynamic impact results for low to intermediate incident energies for both thick and thin specimens. Importantly, they also predicted extremely well the onset of impact delamination for the thick specimens.

However, Figs. 3 and 4 also show that generally the quasi-static tests significantly underestimate the maximum load seen in dynamic impact tests. The impacted specimens generally exhibited a significantly increased resistance to impact fibre damage at higher energies/displacements, giving higher maximum forces and hence an elevated capability to absorb energy (e.g. Fig. 3a). The only exception to this is seen for the thickest specimen ($\O/d$ = 5) in Fig. 3d, where the maximum static and dynamic loads are very similar, although the area under the dynamic curve is still greater, showing a greater ability to absorb the incident energy. In fact it appears that generally as diameter to thickness ratio is decreased that the ability of the quasi-static tests to predict the maximum force at fibre failure improves. However, for the thinnest specimens the fibre failure occurred at a load double that seen for the quasi-static tests. It should be noted here that it is difficult to make valid comparisons with respect to fibre failure load from Fig. 4c and d since dynamic impact tests to 'ultimate' fibre failure were not possible due to the upper limit of incident energy achievable by the impact machine with the current setup (207 J).

It is interesting to now make some comparisons with the work of Zhou and co-workers [3,37,38] which was a part of a wider study of the behaviour of thick GRP laminates. Quasi-static and impact test results were compared for 100 mm diameter specimens of plain-weave fabric E-glass reinforced polyester laminates, and although similar to the present work, that of Zhou et al concerned higher fibre volume laminates (60%) cured in a press at elevated temperature. Also, a flat 20 mm diameter impactor was used (as opposed to the hemispherical one used here) which gave a ply shear-out fibre failure maximum load damage mechanism. No further materials information, such as the lamination method or whether pre-impregnated, could be disclosed due to commercial sensitivity. 10 mm and 25 mm thick laminates were used, which will be referred to here by their diameter to thickness ratios ($\emptyset/d$ = 10 and 4, respectively). Both thicknesses of laminate would fall within the definition of 'thick' specimens as defined in the present study, and the bilinear force–displacement behaviour seen in both cases reflected this.

For the $\emptyset/d$ = 10 specimens, up to the onset of delamination and for intermediate incident energies/displacements the force–displacement behaviour of both quasi-static and impact tests was very similar ([37], Fig 5a). At higher energies/displacements the impact response became stiffer and reached a higher maximum load (on average 36% greater [3], Fig 5.14). For the $\emptyset/d$ = 4 specimens the equivalent plot ([37], Fig 5b) showed a similar behaviour, although both un-delaminated and delaminated impact responses were slightly stiffer. Again the impact response reached a higher maximum load, in this case on average 22% greater ([3], Fig 5.14). In all cases the delamination threshold was the same for impact and quasi-static testing ([3], Fig. 5.13).

Hence, although only considering thicker specimens as defined here, and slightly different material systems and impact set-up, the findings of Zhou et al concur with those for WR laminates of the present study; i.e. that quasi-static testing predicts well the initial to intermediate impact response and the onset of delamination, but generally underestimates the maximum loads at fibre failure.

Fig. 5 compares the quasi-static and impact results for the CSM laminates of the present study. As for the WR laminates, at low to intermediate incident energies/displacements quasi-static results accurately predict the dynamic impact behaviour, as they do for the onset of delamination in the thicker specimens, but the dynamic maximum force at fibre failure and total capacity for energy absorption are both comprehensively underestimated (around 50% of the force) by the static tests.

Similarly, the equivalent plots of Fig. 6 for the cross ply specimens also show that the quasi-static tests give a good approximation of the dynamic force-deflection behaviour at low to intermediate incident energies. However, there is some evidence that the quasi-static test exhibit a very slightly reduced stiffness. Since this reduced stiffness is common for both hand laid-up and infused laminates, it can be inferred that this is not an effect of the production method, but is due to the cross-ply fibre architecture of these specimens. The behaviour of all cross-ply specimens may be characterised as ‘thin’ with membrane effects dominating, although intermediate behaviour with some evidence of delamination is visible in the static results of the 10-ply specimens. As will be further discussed later in this section, this behaviour may well have been obscured by signal oscillations and not identified if only impact tests had been completed. Again, maximum impact forces at fibre failure are significantly higher than (double) those of static tests.

In summary, for the materials considered here, quasi-static tests can predict well the impact force–deflection behaviour at low to mid impact energies. In terms of impact damage resistance, the most important initial damage mode, delamination, is also very well predicted by static testing. Hence, for the materials and impacts studied here, static tests can be used to give valid valuable design information. Although, the ‘ultimate’ impact fibre failure of thinner specimens is comprehensively underestimated (in terms of both maximum force and irreversibly absorbed energy) by the quasi-static tests, given the uncertainties in trying to assess both the nature and severity of the relevant impact event(s) that might be seen in-service this may not be a huge disadvantage since it would provide an inbuilt factor of safety. Much better prediction of the maximum impact force, if not the absorbed energy, is seen for static tests for very thick specimens. Also, even if impact testing is thought to be necessary, resources may be saved through initial static tests to identify the delamination point and make a conservative estimate of the start of fibre failure, ensuring that only expensive impact tests of the most pertinent incident energies are conducted to efficiently give the dynamic response.

It is also probable that quasi-static tests will be sufficient to rate different materials against each other without having to resort to impact tests, but this would have to be explored further. Further work would also be needed to investigate whether the impact delamination area is sufficiently well predicted by the static tests if the present method is to be extended to include the estimation of impact tolerance using specimens damaged through quasi-static simulations of the impact event.

Valuable inferences as to the nature of strain rate effects may also be made through the comparisons between quasi-static and impact test results discussed above, although care must be taken here due to the inherent difficulties in interpreting and conditioning the impact results with their associated signal oscillations. Since impact and static undamaged and delaminated impact responses, and the load at which delamination occurs, of these E-glass/polyester materials are not significantly different it follows that these behaviours are not significantly affected by strain rate effects. However, the fact that large differences between impact and static fibre failure loads were seen indicates that the mechanisms behind this failure mode are significantly affected by strain rate effects. The fact that this fibre failure strain rate effect appears to be less significant for the thicker specimens also indicates that contact initiated failure is not as strain rate dependant as the tensile dominated back-face fibre failure as observed for the thinner specimens.

These findings could go some way to explain the fibre failure size effects seen in the authors’ previous scaling study [15] where fibre failure was delayed (i.e. only seen at higher energies) at smaller scales, which were unavoidably subjected to higher strain rates since it is impossible to scale time. The fact that different responses and failure mechanisms could have varying sensitivities to strain rate would also explain why widely differing strain rate effects for GRP have been seen (e.g. [37,39]).

Quasi-static testing also has the advantage that the force signal oscillations which may obscure vital information in impact results are not present. These types of oscillations may occur due to vibrations in the test equipment itself, in which case they are not relevant to the material response, or could be due to inertia effects and vibrations around the contact stiffness of the plate, in which case they are relevant [1,40]. Here, oscillations of the same frequency were seen in the force signal after the impactor and plate had parted company, indicating that the vibrations were 'ringing' in the machine, and hence were not relevant.

The data may be filtered to remove these oscillations, but especially because the vibration may be significant in comparison to important features within the impact response signal, this may well lead to some loss of accuracy (through unwanted associated transformations of the data such as phase-shifts), and can even obscure some important features, for example the previously mentioned onset of delamination in Fig. 6 for 10-ply specimens. In fact it can be seen from Figs. 3 and 4 that the load at which delamination occurs (corresponding to a sudden reduction in stiffness) can be identified with much greater ease and confidence from the quasi-static results than from the impact data in all cases.

A strong relationship between this 'critical delamination force' (P_{crit}) and the laminate thickness (h) to the power of 3/2 has been found for various different material systems by various authors [18,41–45]. Davies et al. [37,46,47] 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:

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

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

Davies et al used this approach fairly successfully for carbon epoxy [46], but did not obtain satisfactory results for high fibre-volume fraction glass polyester laminates [37]. Cartié and Irving [41] obtained such good correlation using this method for CFRP that they advocated the use of impact testing to determine G_{IIc}. Christoforou [42] also used Eq. (1) to define the onset of delamination. Sutherland and Guedes Soares [18] used this model to successfully model the onset of delamination of WR E-glass/polyester circular plates, although a ln–ln plot gave a slope of 1.66 instead of the 1.5 expected from Eq. (1). The equivalent plot for the static WR data presented here is given in Fig. 7.

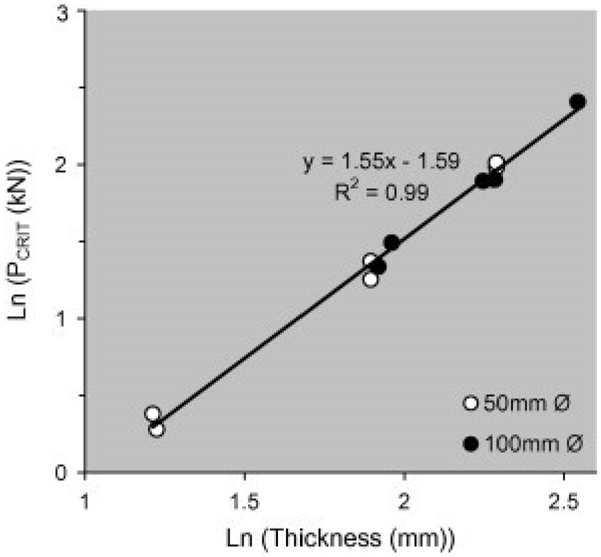

Fig. 7. Quasi-static WR critical delamination forces.

In Fig. 7 it can be seen that the statistical fit is excellent (R^2 = 99%) and further that the slope of the plot is much closer to the value of 1.5 expected from Eq. (1). This latter point is thought to be because of the increased accuracy of identifying the delamination point from these static results, which do not exhibit obscuring force signal oscillations and thereby also avoid the potential errors inherent in dynamic data filtering.

The following expression, which also predicts that P_{crit} varies linearly with $h^{3/2}$, was derived assuming a greatly simplified shear stress distribution and that the delamination occurs as the interlaminar shear strength (ILSS) is exceeded:

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

The expression was originally developed and used successfully by the authors [2] to model the observed change from Hertzian power law to linear indentation behaviour (which was assumed to occur as delamination occurred) for indentation tests on specimens fully supported on a thick steel bed. However, Yang and Cantwell [45] also successfully applied Eq. (2) to model the critical delamination force for impact tests on simply supported cross-ply E-glass/epoxy circular specimens, and used it to explain the variation of delamination force they observed with indentor radius R_1.

As seen in Fig. 7, although the relationship between P_{crit} and $h^{3/2}$ predicted by Eq. (2) is very strong for the present static WR results (as discussed previously), here there is no significant variation of delamination load with the indentor radii considered here (5 and 10 mm for the 50 and 100 mm diameter plates respectively). Why this behaviour is different to that seen by Yang and Cantwell is not clear, although the two studies consider both different materials and specimen boundary conditions. There is also scope for the development of Eq. (2), since it assumes a contact radius dependant only on the Hertzian contact and not also on the subsequent linear contact behaviour actually observed [2], and also does not consider the effect of the rough laminate surface. Further work is required in order to clarify this aspect of the behaviour seen.

5. Conclusions

Both impact and quasi-static tests using identical specimens and experimental set-ups have been carried out in order to evaluate the validity of using more economical quasi-static testing to predict the dynamic impact behaviour of marine GRP composites. This has been studied for a selection of common marine composites; namely woven roving, chopped-strand mat and cross-ply, hand laid-up and infused, E-glass polyester laminates, which enable the validity of the approach to be evaluated for a range of the most frequently used marine laminates.

For both static and dynamic tests the damage progression seen was that of the sudden appearance of an internal delamination at very low incident energy/displacement, followed by fibre failure (leading to penetration and perforation) at much higher incident energy/displacement. The onset of delamination could be identified from the force–displacement plots as a sudden drop in stiffness for all but the thinnest specimens, where membrane forces dominated. Fibre failure in the thinner specimens initiated on the back face due to global plate deformations, for the thicker plates fibre failure was front face, contact initiated.

For all material systems considered here, 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, and hence would provide a valid method of predicting this important initial impact damage resistance.

However, the onset of fibre failure occurred significantly earlier in the quasi-static tests than for impact tests, where a higher (around double) maximum force and hence greater capacity for energy absorption was observed. An exception to this was seen for the thickest specimens, where fibre damage occurred at similar loads for both static and impact tests (although impact tests were still seen to irreversibly absorb significantly more energy).

Quasi-static testing avoids the problems associated with the filtering of, and/or the obscuring of important features by, force signal oscillations which were often significant but not relevant to the material response.

The ‘critical’ force at which delamination initiated showed a very strong linear relationship with laminate thickness$^{3/2}$ as predicted by two simplified models. However, no significant variation of this force with indenter radius was measured, although only a very small range of radii was considered.

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

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 impact resistance design variable. However, if fibre failure and total energy absorption capacity is required, then static tests will give conservative estimates, except for the thickest specimens. In all cases, quasi-static testing can provide valuable input to ensure efficient planning of any subsequent dynamic testing.

Further work is required to verify if quasi-static testing is sufficient to rate different materials in terms of impact resistance, to investigate the slightly lower quasi-static stiffness of cross-ply laminates seen, to explore the relationship of the delamination load with impactor radius, to develop the delamination load model predicting this load with respect to contact behaviour, and to further clarify the strain-rate effects indicated for fibre damage mechanisms.

Further work would also be needed to investigate whether the impact delamination area is sufficiently well predicted by the static tests if the present method is to be extended to include the estimation of impact tolerance using specimens damaged through quasi-static simulations of the impact event.

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