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Influence of Matrix Ductility and Fibre Architecture on the Repeated Impact Response of Glass-Fibre-Reinforced Laminated Composites

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Abstract. This paper describes the results of falling weight impact tests on glass-fibre-reinforced laminates. The test program consisted of (i) falling weight impact tests for the determination of the penetration energy and the influence of laminate construction on damage development and (ii) repeated falling weight impact tests for the determination of the impact fatigue lifetime and damage development under repeated impact conditions at sub-penetration energy levels. The objective of this work is to compare the impact behaviour of cross-ply laminates based on a brittle unsaturated polyester resin and a more ductile vinyl ester resin system and two types of glass reinforcement, i.e. woven- and multiaxial non-crimp fabric. The penetration energy of the various composite laminates appeared to be mainly influenced by the type of reinforcement, whereas damage development during (repeated) impact is strongly influenced by both fibre architecture and resin. No significant effect of the different material parameters investigated on the number of impacts to penetration (impact fatigue lifetime) is observed. Especially when the repeated impact energy is normalised with respect to the penetration energy, all laminates showed similar behaviour.

Key words: glass-fibre-reinforced plastics, woven fabric, non-crimp fabric, impact strength, repeated impact, impact fatigue, damage, delamination.

1. Introduction

Upon impact loading, transverse cracking, delaminations, fibre/matrix debonding and fibre fracture are the potential failure modes in laminated composites. It has been demonstrated that damage due to impact substantially reduces the residual strength after impact of a composite structure, even when damage cannot be visually observed [1–3]. The principal mechanism of compressive strength reduction is local buckling of the sub-laminates formed in the delaminated area [4]. In tensile loading the strength reduction mechanism is dominated by fibre fracture. For

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these reasons, impact damage is generally recognised as the most severe threat to composite structures [5, 6]. The impact resistance of a composite material can be optimised with respect to different end-use requirements. Important criteria are:

- Energy absorption
- Damage resistance
- Damage tolerance

These approaches are to some extent conflicting. The first approach often involves *energy absorption* processes such as fibre breakage, delaminations, debonding, pull-out, etc. The latter two, however, are controlled by *energy storage* processes other than damage. Several attempts were made to improve the impact behaviour of laminated composites. The main developments in toughened composite materials, focus on improved damage resistance or damage tolerance and include:

- Ductile matrices: Modification is established through the addition of rubber or thermoplastic compounds to the matrix [7, 8]. Another example is the use of thermoplastic matrices, e.g., the high performance thermoplastic composite system APC-2® based on a polyether-etherketone (PEEK) matrix reinforced with carbon fibres [9].
- Hybridization: Modification is established through the fibre reinforcement. By combining relatively brittle fibres (read: carbon) with more high strain to failure fibres such as glass, aramid or high-performance polyethylene both energy absorption [10–15] and damage resistance or damage tolerance [16–18] can be improved.
- Interleafing: This idea of composite toughening was introduced by American Cyanamid and involves the incorporation of discrete layers of a high shear strain resin at the lamina interfaces thus giving the composite the ability to undergo higher shear deformations without forming delaminations [19].

The above mentioned toughening concepts were in most cases applied to relatively brittle aerospace grade carbon-fibre-reinforced plastics (CFRP). Less studies were directed towards glass-fibre-reinforced plastics (GRP) composites such as E-glass/unsaturated polyester. Previous studies showed that, in addition to the toughening concepts mentioned above, the impact behaviour of laminated composites is also influenced by the architecture of the 2D reinforcement [20–22].

The present research was part of an extensive European research programme (EUCLID RTP 3.8) aiming at the development of a technical base for large-scale use of GRP in naval applications such as vessels. The research described in this paper had two objectives. First, the determination of the penetration resistance and the damage development during penetration of a number of thin section GRP laminates (energy absorption) and secondly, the repeated falling weight impact behaviour or impact fatigue behaviour of the same set of laminates at sub-penetration energy levels, including impact fatigue life and damage development during repeated impact (damage resistance/damage tolerance).

Impact tests were performed on a number of GRP laminates. Material parameters that have been studied are:

- (i) Influence of *fibre architecture*: composite laminates were manufactured based on either E-glass fibre woven- or multiaxial reinforcements.
- (ii) Influence of *matrix ductility*: composite laminates were manufactured based on two types of resins, i.e. a 'brittle' unsaturated polyester resin and a more 'ductile' toughened vinyl ester resin system with tensile failure strains of 3% and 12%, respectively.

Previous studies on the influence of reinforcement architecture and matrix ductility have been mainly focused on single hit impact tests. Again most investigations focused on aerospace type of CFRP and very few studies were directed towards GRP.

Curtis and Bishop [20] compared the mechanical properties including, tensile properties, notched strength and damage tolerance under non-penetrating impact conditions of woven CFRP with those of cross-ply composites based on unidirectional (UD) prepregs. Results showed the highest tensile strength and stiffness for the UD based material in the case of [0, 90] lay-ups. Impact damage (read: delaminated area) as a result of non-penetration falling weight impact tests (FWIT) was, however, significantly lower for the woven material. Delaminated areas in woven composites showed a more circular damage area, whereas in the case of UD's extensive splitting along the fibre direction at the back surface ply resulted in a highly non-circular damage area. This reduction in damage area in the case of woven composites resulted in a significant improvement in residual tensile and, especially, compressive strengths after impact (CAI). Another study by Winkel and Adams [21] on carbon-, aramid- and E-glass/epoxy focused on full-penetration FWIT and reported the highest energy absorption in the case of cross-ply laminates based on UD's for all laminate configurations investigated. The large difference in energy absorption between GRP composites based on woven and UD's could be explained by the differences in strength and stiffness. Since the flexural failure energy in the case of a beam structure is proportional to the quantity σ^2/E and the highest tensile strength was reported for the cross-ply material, the impact energy was higher for the laminates based on UD's. The optimal type of fibre reinforcement for maximum *penetration energy* as reported by Winkel and Adams [21], i.e. cross-pplies based on UD's, and the optimal reinforcement for *damage resistance/damage tolerance* as reported by Curtis and Bishop [20], i.e. woven fabric, showed once more that materials should be optimized either for energy absorption or damage tolerance and that both types of approach can, to some extent, be conflicting.

Studies on the influence of matrix effects on impact performance of composite materials focused mainly on damage tolerance. Generally, toughened matrix systems with a higher strain to failure yield a reduction in the extent of the damage area and consequently improved residual strength after impact. Good correlations are found between damage area (and hence CAI) and mode-II interlaminar tough-

ness [23, 24]. Although the ductility of the matrix material significantly affects the damage tolerance of the resulting composites under non-penetrating FWIT, matrix effects are less predominant with respect to energy absorption during penetration. In the case of full-penetration most of the energy absorption is the result of fibre breakage [25, 26]. Even in the case of tough thermoplastics such as PEEK in the case of APC-2[®], only a relatively small increase in total impact energy ($\sim 20\%$) was obtained compared to a brittle epoxy based CFRP system [27].

In certain practical situations like slam impacts on boat hulls, a composite can be subjected to repeated impacts. Relatively few studies have been directed towards the problem of repeated impact or impact fatigue of laminated composites and the corresponding damage mechanism. Again also here most studies reported in literature are related to CFRP [29–33]. Rotem [30] showed that when a low energy impact was exerted on a laminate, invisible damage might occur as a result of contact stresses between impactor and the laminate. When impacts were repeated, the damage zone grew and caused a reduction in strength and modulus. Jang *et al.* [31, 32] studied the damage mechanisms in response to repeated low-velocity impacts in both thermoplastic (Polyphenylene sulphide, PPS) and thermoset (epoxy) composites reinforced with glass, aramid and carbon fibres. For any composite an incident impact energy threshold could be identified above which delamination would occur at the first impact. As a consequence, both the stiffness and the maximum load of the load-time curve were reduced and were measured as a function of impact cycles. If instead a sub-critical incident energy was imposed on the material, no appreciable property loss would be observed until a critical number of impacts. In this sub-critical stage, matrix cracking preceded delamination as impacts were repeated. Both the number and size of the delamination cracks were found to increase with the number of impacts. Results showed the highest damage tolerance for GRP, followed by aramid composites and then CFRP. The PPS composites possessed a better resistance to impact damage than the epoxy composites. A more recent investigation by Boukhili *et al.* [33] deals with the fatigue impact behaviour of quasi-isotropic carbon/epoxy laminates. Damage growth during the test was monitored by ultrasonic C-scan imaging. The damage area plotted as a function of the number of impacts displayed a multi-stage pattern behaviour, with stage 1 corresponding to matrix cracking in the region of the impactor, stage 2 to a rapid delamination propagation.

2. Experimental

2.1. MATERIALS

The composite laminates used in this investigation were manufactured using the hand lay-up method by DSM·BASF Structural Resins (Zwolle, The Netherlands). From these laminates different test samples were cut with the dimensions 100×100 mm.

Table I. Material codes

Material Code	Resin	Reinforcement
WF/UP	Unsaturated Polyester	Woven Fabric
	Synolite 0288-I-2	Chomarat 830 S 466
WF/VE	toughened Vinyl Ester	Woven Fabric
	Norpol 92-40	Chomarat 830 S 466
MA/UP	Unsaturated Polyester	Multi-Axial stitched fabric
	Synolite 0288-I-2	Devold AMT DB800-EO1
MA/VE	toughened Vinyl Ester	Multi-Axial stitched fabric
	Norpol 92-40	Devold AMT DB800-EO1

Table I shows the resins and reinforcements of the four materials used in this investigation.

Two resins were used for the fabrication of the laminates: a relatively brittle isophthalic polyester resin from DSM-BASF Structural Resins (Synolite 0288-I-2) and a more ductile toughened vinyl ester resin from Jotun Polymer (Norpol 92-40). The polyester resin was cured using 2 wt.% Butanox M50 at room temperature for 24 hours without any applied pressure. Subsequently, the laminates were post-cured for 16 hours at 40°C. The toughened vinyl ester system was cured under similar conditions using 2 wt.% Norpol 9802 and 0.5 wt.% Norpol 9826 as accelerators and 2 wt.% Norpol 11 as a catalyst.

The Chomarat 830 S 466 reinforcement is a glass woven roving fabric with a coarse (2×2) structure, with a yarn width of about 6 mm. The fabric is balanced and yarns in both the warp and weft directions lie alternately below and above two other yarns (2×2 structure).

The Devold AMT DB800-EO1 reinforcement is a multiaxial (non-crimp) stitched fabric with a relatively fine structure. In these reinforcements the E-glass yarns are fully stretched in multiple directions. In this study, biaxial tapes of glass fibres with the fibres oriented in the 0° and 90° directions are used. The stitching yarn, being a very thin glass yarn, runs in the $\pm 45^\circ$ direction. The multiaxial fabric is stitched every 4 mm to keep the reinforcing fibres together. Since the fibres lie straight and flat, layer by layer, stress concentrations as seen in woven fabrics will not occur in these multiaxial stitched fabrics.

The fibre volume percentage of each specimen was determined from the thickness of the specimen and the contribution of the fibres to the composite thickness. The thickness of the fibre reinforcement was determined from the areal density divided by the density of the E-glass fibres (2560 kg/m³). Both the woven fabric and multiaxial reinforcements had an areal density of 800 g/m². All laminates consisted of four plies of fabric with a 0/90 lay-up. The average thickness of the

laminates was 3.4 mm with an average fibre volume fraction of 35%. Because of the hand lay-up method employed all laminates had a relatively low fibre volume fraction.

2.2. IMPACT TESTING

2.2.1. *Penetration Energy*

Full penetration falling weight impact tests (FWIT) were performed using an instrumented falling weight impact tester. Tests were performed on laminates of the dimensions 100×100 mm using a hemispherical dart with a diameter of 10 mm. The laminates were clamped between two plates with a circular opening of 80 mm. Both force versus time and impact velocity just before impact are recorded and transferred to a data-acquisition board in a PC computer. Force was measured using a piezoelectric force transducer. This piezoelectric force transducer allows a convenient tup construction in which the transducer is close to the point of impact. Throughout the testing, the mass (2.85) and the drop heights (2 m) remained constant. Impact velocity just before impact is measured to eliminate (relatively small) effects of cross-head friction. Impact velocities were about 6 m/s, yielding impact energies in the order of 50 J, which is high enough to give full penetration for all laminate configurations. Post-processing of data results in the complete energy history during impact and gives a listing of impact velocity, maximum force, total energy, absorbed energy and maximum deflection. The output provides plots of: (i) force versus time, (ii) velocity versus time, (iii) energy versus time, (iv) deflection versus time and (v) force versus deflection.

At least four specimens of each of a total of four laminate configurations (four different reinforcement/resin combinations) were impacted. After penetration the specimens were C-scanned and visually examined to determine the size and geometry of the (largest) delamination.

2.2.2. *Repeated Impact*

Non-penetrating FWIT's were conducted with the instrumented falling weight impact tester using the same set-up as mentioned above. All four laminate configurations were tested in repeated impact. Impact energies were generated by dropping a hemispherical impactor loaded with a mass of 1.39 kg from different heights varying between 0.6 and 1.5 m.

The energy levels at which the repeated impacts were performed were set at 25, 30, 40 and 50% of the penetration energy. At these fixed energy levels the different laminate configurations were repeatedly impacted until full penetration. Typical incident impact energies varied between 8 and 20 J. In the case of repeated impact only one specimen was used for each impact condition. The complete energy history, similar to the listing given above for the single hit full-penetrating impacts, was intermittently recorded at different numbers of impacts. The evolution

of damage area as a function of the number of impacts was determined from visual observation. After visual inspection at intermittent number of impacts the samples were carefully placed in the same position for the continuation of the repeated impact experiments.

3. Results and Discussion

3.1. FULL-PENETRATING FALLING-WEIGHT IMPACT TESTS

3.1.1. *Penetration Energy*

FWIT were performed to determine the penetration energy of the various laminate configurations. Figure 1 shows a typical force-time curve of a falling weight penetration test. In this case the force-time curve for a MA/VE specimen is shown. After an impact time of about 2 ms the force remains constant, indicating that the penetration process is completed and a remaining frictional force between dart and laminate is measured. For the calculation of the penetration energy, therefore, only the first part of the force-time curve is used. Typically, the force-time curves show linear behaviour up to a certain force. All laminate configurations tested showed a clear deviation from almost linear behaviour at a load around 3000–4000 N. Around this load level delamination is initiated and the laminate responds in a more compliant way with an almost linear secondary modulus up to the maximum load.

Figure 1. Typical force-time curve during penetration for a MA/VE laminate using the FWIT set-up, showing the initiation of delamination and a constant frictional force after penetration.

Figure 2. Penetration energy for the different laminate configurations as measured using FWIT.

The energy stored in the laminates up to this point of initiation of delamination, i.e. the threshold incident impact energy, is in the order of 3 J.

An overview of the penetration energies of all laminate configurations is shown in Figure 2. Energies varied between 34 J for the WF/UP laminate system up to 40 J for the MA/UP laminate. The lowest impact performance was reported for the systems based on woven fabric. Replacement of the woven fabric with multiaxial reinforcements showed an increase in penetration energy, which can be due to the higher strength of the multiaxial material (see Table II for strength data of laminates based on unsaturated polyester) and/or the increase in damage area. The influence of the ductility of the resin on the penetration energy is less clear, i.e. the penetration energy of the 'brittle matrix' MA/UP system is even somewhat higher than that of its 'ductile matrix' counterpart (MA/VE).

In short, the following conclusion can be drawn from these full-penetration impact experiments. In general, the penetration energy of the specimens with the multiaxial reinforcement is up to 17% higher than the specimens with woven fabric. Similar effects were found in another study that dealt with the tensile strength

Table II. Influence of type of fibre reinforcement on mechanical properties of unsaturated polyester based GRP laminates (standard deviations are given in parentheses) [34]

	WF/UP	MA/UP
Tensile strength [MPa]	224 (8)	272 (4)
Young's modulus [GPa]	20.6 (0.5)	19.0 (0.3)
Failure strain [%]	1.4 (0.1)	2.9 (0.5)
Interlaminar shear strength [MPa]	37 (2)	29 (3)

of these materials [34], indicating some correlation between tensile strength and impact energy. These results are also consistent with previous studies on CFRP that showed an enhanced impact performance for cross-ply laminates compared to woven fabric composites due to the higher tensile strength of the non-woven materials [21]. No clear effect of the influence of matrix ductility on penetration energy was observed, which is again in good agreement with previous studies, showing that under similar impact conditions energy absorption is mainly controlled by fibre breakage with only a small contribution from matrix dominated failure modes such as matrix cracking and delaminations [22, 24–26].

3.1.2. Damage Development

Figure 3 shows the size of the (largest) delamination after penetration of the different laminates as obtained from visual observations. In spite of the similarities in penetration energy, significant differences in damage area are observed between the various laminate configurations. Although the multiaxial laminates, possessing the largest damage areas, showed the highest penetration energy it is believed that the contribution of the delaminations to the total energy absorption is relatively small. The main increase in penetration energy in the case of multiaxial based laminates originated from an increase in the maximum peak-force in the force-time trace monitored during the impact event rather than an increase in energy absorbed after the peak-force. The increase in peak-force in the case of multiaxial based laminates indicated once more that the penetration energy is mainly controlled by fibre dominated fracture (strength) rather than matrix dominated failure modes.

As mentioned previously, significant differences in shape and size of the delaminations are observed between laminates based on woven fabric and laminates based on multiaxial reinforcements. The largest delaminations are observed in laminates based on multiaxial fabrics. Compare for example the delaminated areas of MA/UP with WF/UP. Delaminated areas in woven composites showed a more circular damage area, whereas in the case of multiaxials extensive splitting along the fibre direction at the back surface ply and/or plies resulted in a highly non-circular damage area. Generally, the use of woven fabric restricts the extent of the

Figure 3. Size and shape of glass delaminated area after penetration for the different laminate configurations.

delamination, with the coarse fibre bundles acting as crack-stopper. Particularly the splitting along the fibre direction at the back surface layer(s) that occurred in the case of multiaxial reinforcements (see MA/UP and MA/VE) is significantly reduced. Again, these results are in good agreement with previous impact studies on cross-ply UD's and woven fabric CFRP [20].

Besides a significant influence of the type of glass fibre reinforcement, also a large effect of matrix ductility on damage area was observed. In the case of the woven fabric composites, the (circular) shape of the delamination remains the same but is simply reduced in the more ductile resin system (compare the delaminated area of 'brittle matrix' specimen WF/UP with 'ductile matrix' specimen WF/VE). In the case of the multiaxial reinforcements both the size and shape of the delaminated area are affected (compare MA/UP with MA/VE). It should be noted, however, that the width of the largest delamination is not significantly affected by the type of resin. In both cases the length of this crack is similar or slightly larger than the circular opening of 80 mm in the base plate, meaning that here the extent of the delamination is influenced by the test geometry and clamping. Although the resin did not have any (measurable) effect on the extent of the largest split length along the fibres within the outer ply, the use of a more ductile resin did significantly reduce the delamination in the second outer ply. In the case of specimen MA/UP a symmetric damage area is observed with equal crack lengths in the 0° and 90° direction, indicating not only extensive splitting along the fibres at the $0/90$ interface within the outer multiaxial fabric but similar failure in between the

Figure 4. Back tensile face damage of penetrated 100×100 mm laminates.

two multiaxial fabrics. In the case of vinyl ester resin (specimen MA/VE) extensive splitting occurred only within the outer ply, whereas no extensive delamination and splitting occurred in the other plies.

Figure 4 shows photographs of back face tensile damage of penetrated specimens. These photographs show the more localised circular damage area in the case of woven fabric composites (specimens WF/UP and WF/VE). Moreover, they clearly show the extensive longitudinal splitting in the outer ply and/or plies in the case of laminates based on multiaxial reinforcements (specimens MA/UP and MA/VE).

3.2. REPEATED IMPACT TESTS

The main objective of this part of the investigation was to obtain data on the response of GRP laminates to repeated impact or impact fatigue.

3.2.1. Response to First Impact

Prior to the repeated impact tests, the load-time curves obtained for the different specimen in response to the first impact were recorded along with the numerical data of the maximum load and the absorbed energy. If the incident energy of the first impact exceeds a certain threshold energy level, the laminate will be damaged. All samples were impacted at four different energy levels, i.e. 25, 30, 40 and 50% of the penetration energy of each laminate configuration. Full penetration FWIT data indicated already that the energy necessary to initiate delamination damage is approximately 3 J. Typically, the incident impact energies in the repeated impact

Figure 5. Absorbed energy versus impact energy for first impact event: ○ WF/UP, ● WF/VE, □ MA/UP and ■ MA/VE. (Extrapolation of the data to zero absorbed energy yields the threshold impact energy.)

tests were varied between 8 and 20 J, which is sufficiently high to initiate delamination at the first impact. Upon non-penetrating impact the total impact energy can roughly be divided into two parts:

- The *elastically stored energy* in the composite plate which is released after maximum deflection by rebounding of the laminate. This rebounding energy is successively transferred back to the impact body.
- The *energy absorbed* in the composite laminate, which is available for damage and consequently controls the extent of damage.

Next to elastic energy storage and energy absorption by damage a small part of the impact energy will be converted into vibrational energy, heat and friction. In the current test set-up this part is however negligible and will not be considered further.

In Figure 5 the absorbed energy (= impact energy minus elastic energy) is plotted against the impact energy for all laminate configurations. Surprisingly, for all specimens the absorbed energy is similar, meaning that for all composites the same amount of energy is available for damage. Based on these observations no significant differences in damage tolerance between the different specimens should be anticipated. It is interesting to note that extrapolation of the data to zero absorbed energy yields an impact energy of around 4 J, which is close to the threshold energy

Figure 6. Glass delaminated area after first impact event as a function of impact energy: ○ WF/UP, ● WF/VE, □ MA/UP and ■ MA/VE. (Extrapolation of the data to zero delaminated area yields the threshold impact energy.)

for delamination as determined from the full penetration tests (~ 3 J). This means that basically all the energy is stored elastically in the laminate and transferred back to the impactor at impact levels below this threshold energy.

Following the impact tests the laminates were examined visually for the extent of damage. It can be expected that higher levels of absorbed energy result in more damage. Figure 6 shows the glass delaminated area after the first impact as a function of the impact energy. Clearly, large differences are observed in initial damage area. The overall level of damage in all the laminates increased proportional with increasing impact energy. Similar to full-penetrating impacts, also at relatively low energy non-penetrating impacts the delaminated area is the highest for composites based on the rather brittle polyester resin system in combination with the multiaxial reinforcement (MA/UP). The smallest delaminated areas are obtained in the case of systems based on vinyl ester resin. At sub-penetration impact levels the effect of the type of reinforcement on the extent of the damage is less profound as in the case of full penetrating impacts (see Figures 3 and 4). Again, the data can be extrapolated to an impact energy, which is in the order of the threshold energy for delamination.

In Figure 7 the glass delaminated area is plotted as a function of the absorbed energy. As mentioned, the use of absorbed energy as a critical parameter for impact performance should be preferred over total impact energy. Again significant differ-

Figure 7. Glass delaminated area after first impact event as a function of absorbed energy: ○ WF/UP, ● WF/VE, □ MA/UP and ■ MA/VE.

ences are observed in damage area, indicating that the energy needed to create a certain delaminated area (interlaminar toughness) differs strongly between the different types of resin and glass fibre reinforcement.

Impact results showed, at a given absorbed energy, a glass delaminated area in the multiaxial composite (MA/UP), being at least 50% higher than that in the woven fabric composite (WF/UP). These results suggest that the multiaxial materials exhibit the lowest interlaminar properties. These results seem to correlate well with the short beam shear strength data, which is significantly lower for the multiaxial material. Since the delamination (initiation) energy scales roughly with τ^2/E [35], the largest delaminated area at a given absorbed energy is expected to occur in the multiaxial material.

3.2.2. Impact Fatigue Lifetime

All laminate configurations were repeatedly impacted at the same energy level as the first strike until penetration. Figure 8 shows the impact lifetime curve for a MA/VE laminate. Typically, all laminates showed a similar exponentially shaped lifetime curve with only a few impacts to penetration at relatively high energy levels (e.g. 50% of the penetration energy) and a large number of impacts to penetration at relatively low impact energy levels (e.g. 25% of the penetration energy). Moreover, the shape of the lifetime curves suggests that there is a fatigue limit

below which no penetration will occur. It is not clear if this fatigue limit correlates with the threshold value for delamination. However, based on the data obtained so far there is an indication that, at least for most practical situations, this fatigue limit (~ 9 J) is higher than the threshold value for the initiation of delamination (~ 3 J). In order to be able to identify the true impact fatigue limit clearly more low energy impact data at large number of repeats are needed.

For most laminate configurations no significant differences in the number of impact to penetration are observed. The similarity in relative resistance against impact fatigue for all specimens tested is clearly visualized in Figure 9, when the number of impacts to penetration is plotted as a function of the normalized impact energy. Especially when the (repeated) impact energy is normalized with respect to the penetration energy, all composites show the same behaviour, resulting in a sort of 'Master-Curve' for impact fatigue lifetime.

3.2.3. Damage Development During Repeated Impact

Damage development of a large number of fibre composites subjected to impact fatigue has been examined. For a given material, there usually exists a critical impact energy, above which a significant delamination crack will initiate in response to a single impact. In our experiments, delamination was observed in all specimens after the initial impact. When impacts are repeated this delaminated area will grow. These observations are shown in Figure 10 for all laminate configurations. In this

Figure 8. Impact fatigue lifetime curve for a MA/VE laminate.

Figure 9. Impact fatigue lifetime curve normalized by its penetration energy, showing similar behaviour for all laminate configurations: ○ WF/UP, ● WF/VE, □ MA/UP and ■ MA/VE.

graph the glass delaminated area with increasing number of impacts is plotted for a low energy repeated impact test (25% of the penetration energy). For most woven fabric specimens, the glass delaminated area increased gradually with the number of impacts. Only in laminates based on multiaxial reinforcements a clear two-stage damage growth process is active. The damage area remains constant at low impact numbers and increases rapidly at high ($n > 10$) impact numbers. Similar multi-stage delamination pattern behaviour has also been reported by Boukhili *et al.* [33], where stage 1 corresponds to matrix cracking in the region of the impactor and stage 2 to rapid delamination propagation. It is also shown in Figure 10 that, for systems based on the ductile vinyl ester resin, deviations between the laminates based on woven fabric and multiaxials only occur at high impact numbers, whereas at low impact numbers the delaminated areas in both laminates are the same. This is in good agreement with the similarities in delaminated area at sub-penetration impact levels as shown in Figure 6 and the differences in delaminated areas at full penetration impact levels as shown in Figure 3 and 4.

Figure 11 shows the delamination growth rate for a MA/VE laminated composite, which was repeatedly impacted at different percentages of the penetration energy. It is shown that with increasing impact energies the delamination growth curve shifts towards lower number of impacts where the shape of the curve remains basically the same, indicating that the damage mechanisms in stage 1 and 2 essentially remain the same. As expected, higher impact energies promote rapid (stage 2)

Figure 10. Delamination growth as a function of number of repeated impacts for low energy repeated impacts (25% of the penetration energy), showing a gradual increase in delaminated area for woven fabric composites and a two stage damage growth process for the multiaxial composites: ○ WF/UP, ● WF/VE, □ MA/UP and ■ MA/VE.

delamination growth, leading to a shortening of the stage 1 damage process where only localised matrix cracking is observed.

Figure 12 shows typical force-time curves at different number of repeated impacts for a MA/VE laminate. For clarity, curve fits are shown of actual force-time traces. After the first impact, the maximum force increases initially. Due to matrix cracking of the resin rich top layer the local stiffness of the laminate increases, resulting in an increase in peak force. When the impacts are repeated, the maximum load starts to drop dramatically at relatively high impact numbers. This drop in maximum load is the result of a lowering of the global laminate stiffness due to delaminations as well as a reduced local rigidity at the point of impact due to fibre breakage. Simultaneously, the absorbed energy will increase due to the increase in local fracture processes such as fibre breakage. Figure 13 shows the maximum force as a function of the number of impacts for a MA/VE laminate. Typically, at low energy levels (25% of penetration energy) the maximum force remains relatively constant up to approximately 20% of its lifetime (stage 1). Next, the maximum force starts to drop as a result of extensive delamination growth (stage 2a), whereas at relatively high impact numbers (above 70% lifetime) a dramatic drop in peak load is observed as a result an additional fibre breakage process in the vicinity of the impactor (stage 2b).

Figure 11. Damage growth in MA/VE laminates as a function of number of repeated impacts at different energy levels (25, 30, 40 and 50% of the penetration energy), showing the shift in stage 1 to stage 2 transition to smaller number of impacts with increasing impact energies.

Figure 12. Typical force-time curves for a MA/VE laminate at different number of impacts, indicating the reduction of peak force at high impact numbers.

Figure 13. Maximum force as a function of number of low energy (25% penetration energy) repeated impacts for a MA/VE laminate, indicating the onset of rapid delamination (stage 2a) at approximately 20% lifetime and extensive fibre breakage in the vicinity of the impact (stage 2b) at approximately 70% lifetime.

This effect is also visualised when the absorbed energy for the same MA/VE laminate is plotted as a function of impact fatigue lifetime (Figure 14). It is shown that the absorbed energy remains nearly constant in stage 1, whereas a moderate increase in absorbed energy due to delamination is observed in stage 2a and a strong increase just before penetration due to additional fibre breakage. This sudden change in maximum force and absorbed energy, due to extensive fibre breakage in the vicinity of the impact, at approximately 70% lifetime was observed for all the other laminate configurations.

4. Conclusions

- The penetration energy of the specimens with stitched multiaxial reinforcement was higher than that of specimens with woven fabrics.
- No clear effect of the influence of matrix ductility on penetration energy was observed, indicating that energy absorption is mainly fibre controlled with only a small contribution from matrix dominated failure modes such as matrix cracking and delaminations.
- In spite of the similarities in penetration energy, significant differences in damage area are observed between the various laminate configurations. Large

Figure 14. Absorbed energy force as a function of number of low energy (25% penetration energy) repeated impacts for a MA/VE laminate, indicating the onset of rapid delamination (stage 2a) at approximately 20% lifetime and extensive fibre breakage in the vicinity of the impact (stage 2b) at approximately 70% lifetime.

differences in shape and size of the delaminations are observed between laminates based on woven fabric and laminates based on multiaxial tapes, i.e. the largest delaminated areas were observed in the case of multiaxial tapes. Generally, the use of woven fabric restricts the extent of delamination, with the coarse fibre bundles acting as crack-stoppers. Similarly, relatively large differences in damage area are observed between laminates based on a 'brittle' unsaturated polyester resin and laminates based on a more 'ductile' vinyl ester resin system, i.e. the largest delaminated areas were observed in the case of laminates based on unsaturated polyester.

- In the case of non-penetrating impact no significant differences in absorbed energy (= impact energy minus elastic energy) are observed. Differences in the investigated material parameters, i.e. glass reinforcement architecture and type of resin, do not result in a change in energy absorption mode.
- For most laminate configurations no significant differences in the number of impacts to penetration (impact fatigue lifetime) are observed for the different laminate configurations. When the (repeated) impact energy is normalised with respect to the penetration energy, all composites show the same behaviour, resulting in a 'Master-Curve' for impact fatigue.

- For most specimens the glass delaminated area increased gradually with the number of impacts. Only in laminates based on multiaxial tapes a two-stage damage growth process is active, where stage 1 corresponds to matrix cracking in the region of the impactor and stage 2 to rapid delamination propagation.
- When the impacts are repeated the maximum force decreases, whereas the absorbed energy increases. Typically, at low repeated impact energy levels (25% of the penetration energy) the maximum force started to decrease and the absorbed energy levels started to increase dramatically at 70% lifetime, indicating that only in the last part of the impact fatigue-life extensive fibre breakage occurs in the vicinity of the impact.

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