A HOLLOW FIBRE REINFORCED POLYMER COMPOSITE ENCOMPASSING SELF-HEALING AND ENHANCED DAMAGE VISIBILITY.

Ms. Jody W.C. Pang, *Dr. Ian P. Bond

University of Bristol, Department of Aerospace Engineering, Queen's Building, University Walk, Bristol. BS8 1TR. UK. Tel: +44(0)117 928 8662 Fax: +44 (0)117 927 2771 E-mail: I.P.Bond@bristol.ac.uk

ABSTRACT

The aim of this study was to develop a novel fibre reinforced plastic which employed a biomimetic approach to undertake self-repair and visual enhancement of impact damage by a bleeding action from filled hollow fibres. The results of flexural testing have shown that for the lay-up investigated, a significant fraction of flexural strength lost after impact damage can be restored by the self-repairing effect of a healing resin stored within hollow fibres.

The release and infiltration of an UV fluorescent dye from fractured hollow fibres into damage sites within the internal structure of the composite has been successfully demonstrated. It has been correlated with respect to the ultrasonic C-scan NDT/NDE technique and shown to be an effective method of quickly and easily highlighting damage at the surface that requires further investigation. This could be of particular benefit where rapid visual inspection of large surface areas (e.g. wing skins) is required.

Keywords

Polymer-matrix composites (A), Smart materials (A), Fibres (A), Damage tolerance (C), Self-Repair

1. INTRODUCTION

The field of fibre reinforced composite materials has grown rapidly since their introduction such that over 20 million tons are now produced every year for a variety of aerospace and other applications. However, concerns remain about the structural integrity of composite materials following impact loading, as such materials are susceptible to cracks or delaminations that form deep within the structure. These cracks are extremely difficult to detect and repair by conventional methods is often impossible. In addition to compromising the material's structural properties, these cracks also provide sites for activities such as moisture swelling which further degrade material performance [1]. Low velocity impact damage can cause a substantial reduction in the undamaged structural strength of polymer matrix composites. Such damage may be caused by dropped tools, ground handling equipment and hailstones. If this damage

* Corresponding Author

occurs on a macroscopic level it may be easily detected and repaired, but microscopic damage such as matrix micro-cracking, fibre-matrix debonding and delamination is more insidious and may go unnoticed and unrepaired [2] giving rise to Barely Visible Impact Damage (BVID). One of the key factors limiting current design allowables is the strain at which there will be no growth of BVID. Self repairing composites offer the potential for a substantial improvement in resistance to delamination propagation, allowing the outstanding properties of fibre reinforced plastics to be more fully exploited.

The concept of self-repair is that a damaged structure is repaired by materials already contained within it, analogous to the biological healing process in living organisms. The key is that no external action is required, unlike conventional repair. The technology must sense and respond to damage, restoring the material's performance without affecting the overall properties of the system. This would make the material safer, more reliable, longer lasting, and require less maintenance and thus reduce costs.

The use of functional components stored inside composite materials to restore physical properties after damage has been advocated by several workers. Dry [3-6] adapted the concept of a biological self-healing approach, i.e. bleeding, for use in a concrete. This idea involved the storage of repair components inside vessels distributed within a concrete specimen which after sustaining damage will release a repair medium. Methyl methacrylate liquid was used inside hollow porous polypropylene fibres within the concrete, and released from the fibres to reduce concrete permeability. A further investigation was undertaken into the release of crack-adhering adhesive from hollow glass pipettes into the concrete after flexural testing. The adhesive loaded sample demonstrated an ability to carry ~20% more load under a subsequent flexural test. Li *et al.* [7] developed the self-repairing concept and applied it once again to cementitious composites. 'Superglue' (ethyl cyanoacrylate) was used as the healing agent within 500µm diameter hollow glass tubes. The 'capillary effect' was first introduced as a method of filling a hollow glass fibre with healing agent.

The application of a self-repairing concept to fibre reinforced polymer composite materials has been discussed and demonstrated as feasible by several workers. Healing agent storage methods have been developed based on the use of hollow tubes and fibres, particles and microcapsules, all of which can provide an integral healing agent storage capacity. Dry [8-10] has investigated damage-associated matrix microcracking. A single repair fibre was embedded in a polymer matrix and tests performed to visually verify the release of repair agent. Motuku *et al.* [2] developed the concept by considering different critical parameters, such as method of storage (glass, copper and aluminum tubing), and healing agents (vinyl ester 411-C50 and EPON-862 epoxy). The suitability of glass tubing in allowing the release of healing agent into the matrix after fibre breakage was proven. In the work by Dry [10] and Motuku *et al.* [2], dye release accompanied the healing agent, however, this combination resulted in an inability to cure and thus no improvement in mechanical properties was reported.

Bleay *et al.* [11] conducted studies with a composite material self-repairing system. Hollow glass fibre composites were filled with an X-ray opaque dye penetrant and one and two-part curing resin systems. These were then assessed for an ability to perform self-repair and enhance damage detection. A vacuum assisted capillary action filling technique was developed and used to successfully fill the hollow fibres. A variety of treatments were used to draw the resin out of the fibres after impact. The most effective was shown to be the simultaneous application of heat and vacuum. The damage detection method was improved by using a X-ray opaque dye. It not only showed the damaged area, but also the ingress of dye penetrant into the damage zone after impact testing. The post-repair compression strength after impact testing showed about a 10% strength improvement.

Zako *et al.* [12] introduced a method of impregnating small particles (50μm) of thermoplastic adhesive in a glass/epoxy composite laminate. The cure temperature of the epoxy matrix was 110°C. The embedded thermoplastic particles melted when damaged composites were subsequently heated to 120°C for 10 minutes on a hot plate. In subsequent three point bend testing, the load-displacement curve indicated that stiffness was recovered in the repaired specimen.

White *et al.* [13], Kessler *et al.*[14-16], Brown *et al.* [17-19] have all taken a different approach by embedding microcapsules of monomer healing agent throughout a polymer matrix. These microcapsules fracture and release healing agent upon damage. The healing agent (DCPD – Dicyclopentadiene monomer) moves through the matrix and contacts an embedded particulate catalyst (Grubbs' catalyst), initiating 'Ring Opening Metathesis Polymerization'[20] and healing the damage. The unique feature of this healing concept is that it uses a live catalyst, thus enabling multiple healing events. Early efforts [13-15,17] of injecting catalysed monomer manually into damaged plain weave DCB specimens saw healing efficiencies of up to 67% relative to the virgin fracture toughness. This was reduced to 19% when the particulate catalyst was directly embedded into the matrix. More recently, Kessler *et al.* [16] and Brown *et al.* [17-19] have also carried out an investigation into the effect of size and concentration of the catalyst and microcapsules on fracture toughness and also optimised the microcapsule surface morphology, rupture and healing agent release behaviour. Results found that the DCPD healing agent worked very well at a temperature of 80°C[16] giving a maximum healing efficiency of >70%[19].

However, all approaches pose some problems for developing a self-healing composite. Kessler & White [14] report that the virgin toughness of a specimen decreases slightly when an unintended catalyst cluster is found in the matrix. These clusters also contribute to unstable crack propagation. Also, in Zako *et al.* [12] research showed that the voids left after embedded thermoplastic particles were melted and filled a damaged area had an erratic effect on the integrity of the material. Hollow glass fibres were seen to provide a good combination of storage function and mechanical reinforcement by Bleay *et al.* [11]. They avoided some of the detrimental effects on mechanical performance of the host composite associated with particles or microcapsules and acted as both a reinforcement and healing agent reservoir. However, their self-healing effectiveness was shown to be limited by the amount of healing resin that could be stored internally.

The approach taken in this study here requires the deployment of specially developed hollow fibre reinforcement with large internal volume to maximise the storage capacity [21-24]. Hollow glass fibre is an ideal medium for storing healing components as it can simultaneously act as structural reinforcement and potentially offers many other benefits to composite materials [25-27].

During a damage event some of these hollow fibres will fracture thus initiating two processes. Firstly, the enhanced visualization of the damage site by seepage of a highly conspicuous medium (e.g. ultra-violet fluorescent dye) thus aiding the practical inspection for BVID and identifying areas for permanent repair. Secondly, the recovery of properties by 'healing' whereby a repair agent passes from within any broken hollow fibres to infiltrate the damage zone and acts to ameliorate its effect on mechanical properties. This repair process will act to reduce the critical effects of matrix cracking and delamination between plies and, most importantly, prevent further damage propagation.

It is worth noting that in conventional fibre reinforced plastics, the role of a fibre is to add strength and stiffness to the polymer matrix. The introduction of fibre multi-functionality to provide addition roles is an attractive but currently unavailable option [28] and heralds the move towards ‘smarter’ materials.

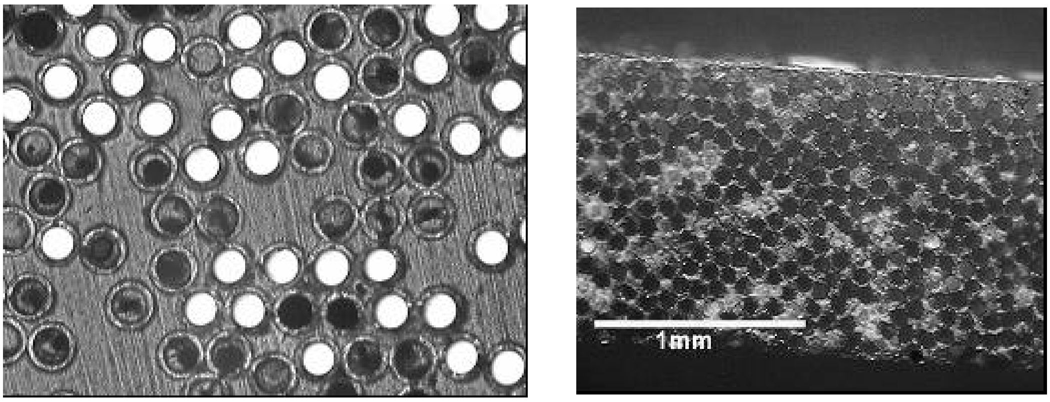
2. EXPERIMENTAL APPROACH

The use of hollow fibres to contain a repair medium has proved difficult to implement to date, largely due to the unavailability of high quality structural hollow fibres [11]. The in-house manufacture and application of such fibres, eliminates the need to incorporate supplementary vessels which compromise composite structural performance, disrupt fibre regularity, act as discontinuities and reduce useful fibre volume fraction. Various methodologies for imparting self-repair are possible, including one-part resins, two part resins in alternating plies, and resin in hollow fibres with the associated hardener in microcapsules dispersed within the matrix.

The aim of this study was to employ a biomimetic approach and fabricate a composite with a 'bleeding' ability. The material used in this study comprised unidirectional hollow glass fibres (60µm external diameter, 50% hollow fraction) in an epoxy matrix in combination with conventional E-glass/epoxy. A 0°/90° lay-up ensured that uncured resin or hardener (mixed with UV fluorescent dye) could be infiltrated into the fibre lumens without combination. Uncured epoxy resin resided within the 0° layers and hardener within the 90° layers. A series of test specimens were produced both with and without resin/dye infiltrated hollow fibre plies. A representative impact damage site was formed in the centre of each specimen and healing was allowed to take place under various 'healing' regimes to determine the efficacy of repair prior to four point bend testing.

2.1 Specimen preparation

Borosilicate glass tubing [Schott DURAN®] is drawn down into 60µm external diameter, 50% hollow fraction fibre using the bespoke fibre making facility at Bristol University. This was created through previous collaborative work with DERA Farnborough (now QinetiQ) and BAE Systems. It has the capability to draw precision solid, hollow and novel shaped glass fibres down to 10µm diameter with >50% hollowness, and processing glasses up to 1500°C. With careful choice and control of preform dimensions, preform feed rate, fibre draw rate and furnace temperature, a highly consistent and concentric hollow fibre is produced with ± 1µm accuracy [21-24], Figure 1. Hollow fibres of smaller diameter (down to 30µm) can be drawn but were found to be inconsistent, in terms of their retained hollowness i.e. <25% hollow, and impractical to manufacture in the quantities needed.



(a) (b)

Figure 1. Optical micrographs of fibres and composites manufactured at Bristol (a) hollow glass fibres of 60μm external diameter with a hollowness of 50% and, (b) the same fibres within a Hexcel 913 epoxy matrix

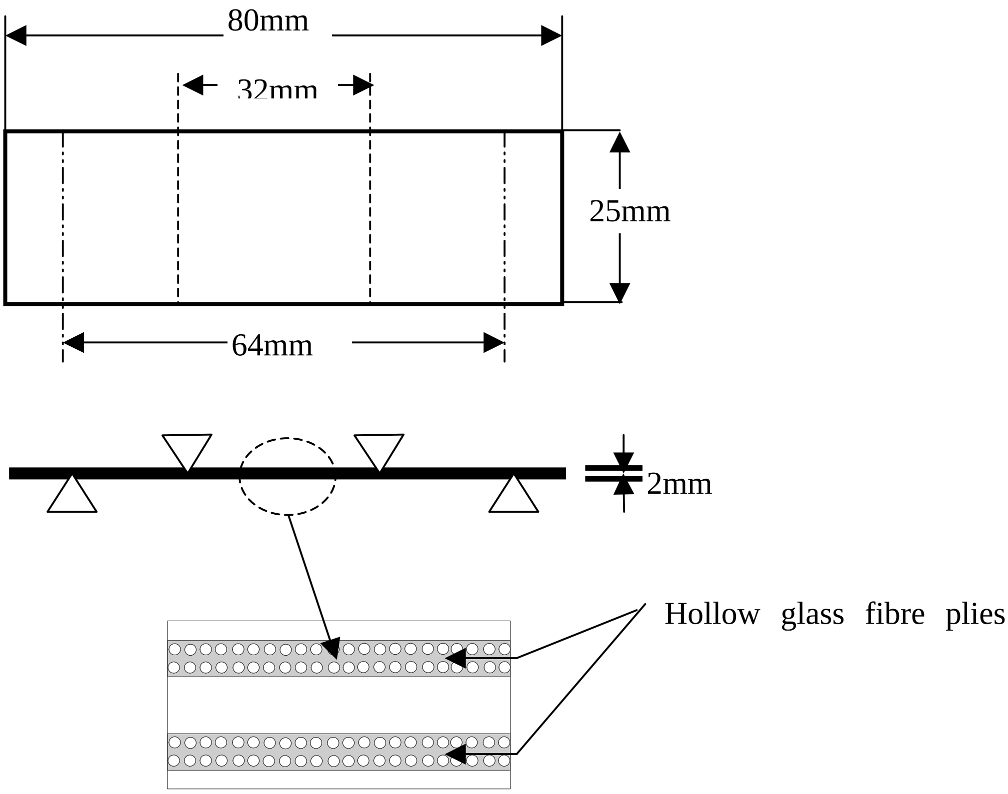


Figure 2. Lay-up configuration and dimensions for 4-point bend flexural testing.

A resin film infusion process is used to produce hollow glass fibre/epoxy preimpregnated tape (prepreg). Hexcel 913 epoxy resin is used as the matrix material. The prepreg contained a nominal gross fibre volume fraction (V_f) of approximately 61.5%. Six laminates of 18 plies (nominal thickness 2mm) were manufactured using a hand lay-up process and cured according to manufacturers recommendations. The lay-up chosen was $\{[90°/0°]_{(solid)},[90°/0°/90°/0°]_{(hollow)},[90°/0°/90°]_{(solid)}\}_S$ to position the hollow plies in the sub-surface of the laminate and provide a fully symmetric arrangement and avoid any detrimental residual stresses. A [90˚/0˚] lay up for the hollow glass plies ensures that uncured epoxy resin (plus fluorescent dye) and hardener can be infiltrated into the 0° and 90° plies respectively. The solid plies were commercially supplied E-glass/913 epoxy resin. These E-glass fibres are typically 12μm in diameter and possess a similar stiffness to the hollow fibres.

The six panels were cut into 80mm (length) x 25mm (width) x 2mm (depth) specimens (Figure 2) using a diamond saw, then a water filled ultra-sonic bath was used to remove any cutting debris from inside the hollow fibre lumens. Care was taken to fully dry specimens after this cleaning process. Four groups of specimens (B, C, D, E) had the 0° hollow plies filled with dilute epoxy resin repair agent (MY750 Ciba-Geigy + 30%/vol acetone) and the 90° plies filled with corresponding hardener. The resin and hardener weight gain per specimen was recorded and used later to normalise the flexural strength test data to an equivalence of 1%/weight for all specimens.

Fibres were filled using a vacuum assisted liquid infiltration technique. After thorough cleaning the specimens were oriented such that one end of either the 0° or 90° exposed fibre ends were immersed, to a depth of a few millimetres, in resin or hardener respectively . A vacuum was then applied to the opposite end of the specimen. The combination of capillary action and vacuum saw liquid drawn into the fibres within a short period of time. The fibres are then sealed using a rapid room temperature cure epoxy putty (ITW Devcon® Magic Bond™) which is manually inserted a few millimetres into the fibre lumens.

2.2 Mechanical Testing

Six specimen groups (A-F) were prepared in order to establish the mechanical behaviour before and after pseudo-impact damage on a self-healing hybrid solid/hollow glass fibre reinforced composite. An objective of the study was to establish the efficiency of repair after a period of time had elapsed. Thus, a series of tests were undertaken at prescribed time intervals. Four-point bend flexural testing, according to ASTM 790M-93, was chosen for simplicity.

Four specimen groups (B, C, D, E) were filled with repairing agent and two groups (A & F) were not. The latter represented undamaged and damaged states respectively. The five specimen groups (B, C, D, E, F) were subjected to impact damage by a process of indentation using a hardened steel hemi-spherical end of 4.63mm diameter with the specimen back face supported by a steel ring, as shown in Figure 3. An Instron 1341 servohydraulic machine was used for both indentation and 4-point bend testing. A PC based data acquisition system was used for all mechanical testing. Indentation was performed under load control at a crosshead displacement rate of 3mm/min to a maximum load of 1200N. This corresponds to an impact energy of approximately 0.6 Joule if the area under the load-displacement curve is integrated.

In order to ascertain the effect of time on repair efficiency, specimen groups B, C, D and E were stored in a desiccator for periods of 0, 3, 6 and 9 weeks before being subject to damage (via indentation) and flexural testing. Immediately after indentation these specimen groups were allowed to undergo a process of self-healing for 24 hours at ambient temperature as this had previously been established [29] as the most simple and effective healing regime. The four-point bend flexural testing was conducted to investigate the efficiency of a bleeding composite to effect a self-repair. Figure 2 gives a schematic of the test geometry. A displacement rate of 3.4mm/min was used for the flexural testing. The impact damaged face of the specimens was oriented such that it was subject to compressive loading.

2.3 Enhancing Damage Visibility

To enhance the ‘bleeding’ process, a conspicuous medium (e.g. UV fluorescent dye) can be added to the healing resin within the hollow fibres to aid inspection for BVID. In order to investigate, validate and calibrate this enhancement of damage visibility, ultrasonic scanning (C type) was employed to compare with the proposed ultra-violet mapping technique (UVMT). Ultrasonic C-scans are widely used as a reliable non-destructive method for composite materials inspection. Thus, it is an ideal method to assess the reliability and effectiveness of the UVMT technique.

Twenty five specimens were prepared according to the manufacturing process reported above, with the exception that an UV fluorescent dye penetrant (Ardrox 985) was added to the fibres instead of repair resin or hardener. These specimens were then divided into five groups and subjected to indentation as described above. Five different indentation forces were applied to the specimens; 800N, 1000N, 1200N, 1400N and 1600N. The equivalent impact energies are shown in Table 1. Two damage sites were created on each specimen in order to provide an average result of ten damage sites for each impact energy. The damage created by the indentation process was then measured using the UVMT and then ultrasound C-scan. The former consists of recording magnified digital images of the damage site under ultra-violet illumination. Efforts were then made to measure and correlate the resulting damage maps from each specimen using the two techniques and image analysis (ImagePro®) software.

Table 1. Correlation of indentation load and impact energy.

Indentation Force (N)	Energy absorbed (J)
800	0.25
1000	0.43
1200	0.62
1400	0.80
1600	1.13

3. RESULTS & DISCUSSION

3.1 Indentation behaviour

Figure 3 shows a cross-section through an uninfiltrated specimen (group F) after indentation, illustrating interface delamination, matrix cracking and hollow fibre fracture. The majority of the impact induced damage is localised within or adjacent to the hollow fibre plies, thus creating an ideal situation for self-repair by the uncured resin within the hollow fibres. The fracture of hollow fibres in the 0° and 90° plies and the mixing of resin and hardener allows initiation of the curing process whilst simultaneously promoting infiltration of the local matrix cracks and delamination by capillary action. A key aspect of this whole self-healing process is that the impact energy must be of a sufficient threshold value to fracture hollow fibre plies. This threshold value can be tailored for any application by the constituents, number and positioning of the repair agent bearing layers within the laminate stack.

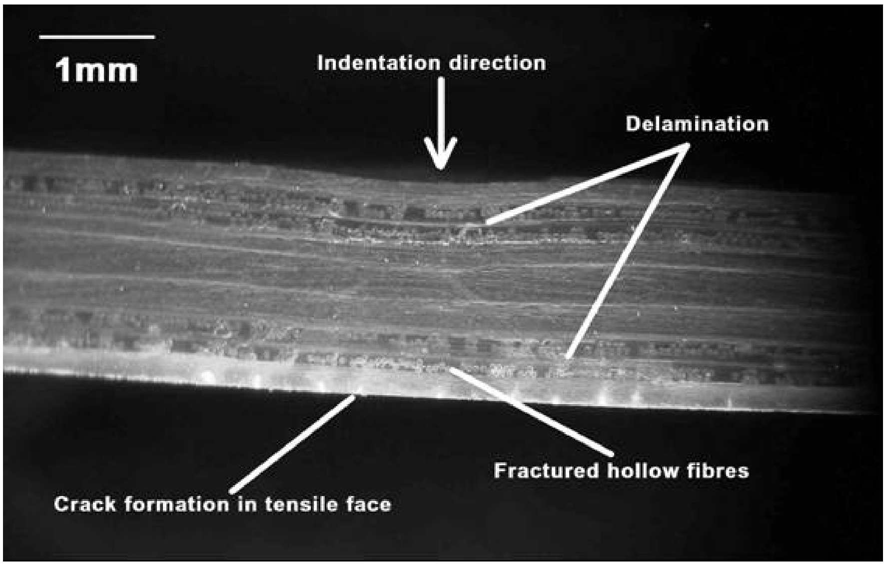


Figure 3. Optical micrograph of cross-section through impact damaged hybrid solid glass/hollow glass/epoxy laminate.

3.2 Four-point bend flexural testing

Figure 4 and Table 2 show the results of four-point bend flexural testing for the six specimen groups. In order to provide a fairer comparison of the test data, flexural strengths for groups B-E have been normalised to a nominal 1%/weight repair resin content within the hollow fibres. This can be justified as the resin content directly affects the extent of damage repair after impact and thus the resulting flexural strength. All testing was undertaken with the damaged face of the specimen subject to compressive loading. This was because resin repair would have negligible effect on the fibre dominated tensile face.

It is clear that impact has a serious effect on flexural strength, as specimen group F (damaged, uninfiltrated) shows a ≈25% reduction compared to group A (undamaged, uninfiltrated). If a process of self-repair is introduced (group B) immediately post-manufacture, it is clear that a significant proportion (93%) of flexural strength can be restored. This is probably attributable to an extensive penetration of damage crack paths (see Figure 3) by the repair resin before the viscosity rise associated with cure progression precludes this process. This self-repairing mechanism is not proposed as a permanent measure to eradicate the effects of damage within a composite but to provide a means to inhibit further damage propagation.

Specimens groups B-E were used to assess the rate of degradation of the repair resin effectiveness over time. Each group of specimens was stored for different periods (0, 3, 6 and 9 weeks) before being damaged, allowed to self-repair for 24 hours under ambient conditions and then tested in flexure. The efficiency of repair is seen to deteriorate markedly over a 9 week period (albeit with a significant degree of scatter). After a 9 week period had elapsed (group E) self-repair was no longer seen to occur. Flexural strength is then shown to be equivalent to a damaged and unrepaired material (group F).

This is probably attributable to the self-repairing agent failing to bleed out from the fractured fibres. Much of this behaviour can be caused by the use of an unoptimised repair resin which includes additional components (UV fluorescent dye and acetone). Although mixing acetone and fluorescent dye with resin led to no observable physical change in the short term, other physical or chemical processes could still occur over an extended period of time. The modified resin is likely to experience discernible deterioration with time, or be unsuited to storage in an uncured state for long periods. Specimen groups C, D and E evidently failed to undergo self-repair, and this is probably attributable to several factors.

In this research, a 30%/wt. acetone dilutent was added to the MY750 epoxy healing resin to reduce the viscosity. This addition is likely to have altered the resin chemistry, inhibiting the polymerisation process and shortening the molecular chains. The presence of acetone in epoxy is also likely to change the macromolecular structure and/or the cross-link density. An investigation into the influence of solvent content in polymer reinforced matrix materials by Buehler & Seferis [30] demonstrated that acetone in resin precursors could lead to alteration of resulting physical properties. A similar finding was obtained by Hong & Wu [31] who claimed that the presence of acetone can alter the reaction mechanism and cure speed of an epoxy system due to the temperature variation resulting from the heat absorbed by solvent evaporation. The consequences of such interactions, within this study, could have rendered the healing resin ineffective after a short period of only 9 weeks.

The quantity of the repair agent stored inside the composite is critical to the self-healing process [11,13,15]. It was found that repair agent weight gain is highly variable between specimens, due to some of the hollow fibre cores being blocked during the specimen preparation process. Glass fragments in the fibre ends could have stopped repair resin infiltrating the fibre even after cleaning in an ultrasonic bath.

The reason for the failure of self-healing occurring over the 9 week test period is unlikely to be attributable to any one factor. The mechanism of healing via a bleeding process from hollow fibre reservoirs requires several stages, the absence of any one can result in no repair. However, these results indicate the importance of choosing an appropriate repair resin which offers ease of infiltration into hollow fibres, the ability to infiltrate and repair a damage zone, simple and controllable cure characteristics and adequate mechanical properties once cured.

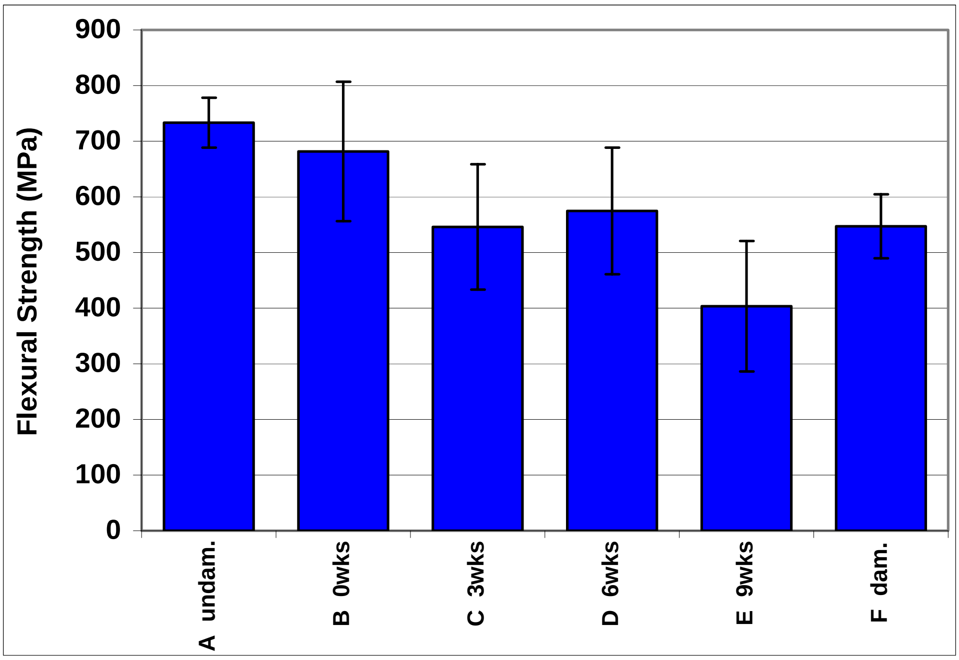


Figure 4. Results of flexural testing for damaged, undamaged and self-repaired specimens after various storage periods (bars denote standard deviation).

Table 2. Results of four-point bend flexural testing for all specimen groups.

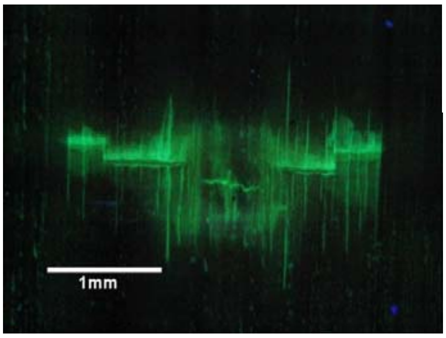
Sample identity	Sample condition prior to testing	No. of samples	Mean flexural strength (MPa)	Standard deviation (MPa)	Percentage undamaged state (%)
A	Undamaged	14	733	45	100
B	Stored 0 wks, Damaged & Repaired	8	682	125	93
C	Stored 3 wks, Damaged & Repaired	7	546	112	75
D	Stored 6 wks, Damaged & Repaired	8	574	114	78
E	Stored 9 wks, Damaged & Repaired	8	404	117	55
F	Damaged	8	547	57	75

3.3 Visual enhancement of damage

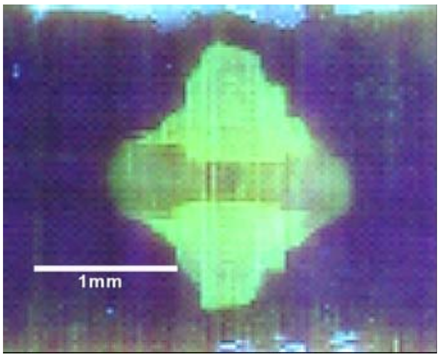
An important aspect in the development of ‘bleeding’ fibre composites is to provide visual enhancement of damage, in particular BVID. The bleeding action of a highly conspicuous dye into the numerous cracks and fissures created by a damage event serves to decorate these sites, increasing their ease of detection in

NDT/NDE. This could be of particular benefit where rapid visual inspection of large surface areas (e.g. wing skin panels) is required.

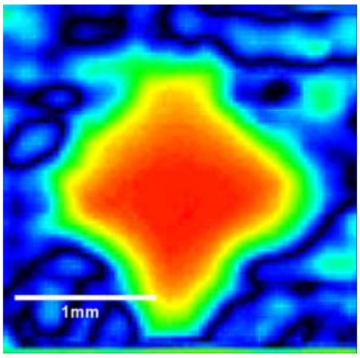
Figure 5 compares three typical views of a damaged (0.8J) specimen identical to those described previously, but containing a UV fluorescent dye (Ardrox 985) within the hollow fibres. Figures 5a and 5b show the respective front (side of impact) and back face views under UV illumination, while Figure 5c shows an ultrasonic C-scan of the same damage site . It is clear that the use of a UV dye is very effective in highlighting a damage site. Also, it appears from Figures 5b and 5c that the damage shown using UVMT correlates very well with that from C-scan. This is further verified by Figure 6 which attempts to quantify and compare the damage areas after various impact energies, measured using UVMT and C-scan. Measurement of damage on the back face using UVMT closely correlates to C-scan, with a reasonably uniform discrepancy of approximately 25%, for the impact energies investigated. Measurement of damage area from the front face using UVMT is less distinctive. However, it is useful in finding and marking a damage site on the surface, offering a rapid and easy technique for highlighting suspect areas for further NDT/NDE.



(a) front face (impact face) view using UVMT



(b) back face view using UVMT



(c) view using C-scan

Figure 5. Comparison of Ultra-Violet Mapping Technique (UMVT) viewed from (a) front and (b) back faces of specimen and (c) Ultrasonic C-scan after impact damage of 0.8J (i.e. indentation @ 1400N). (Note: images not to scale)

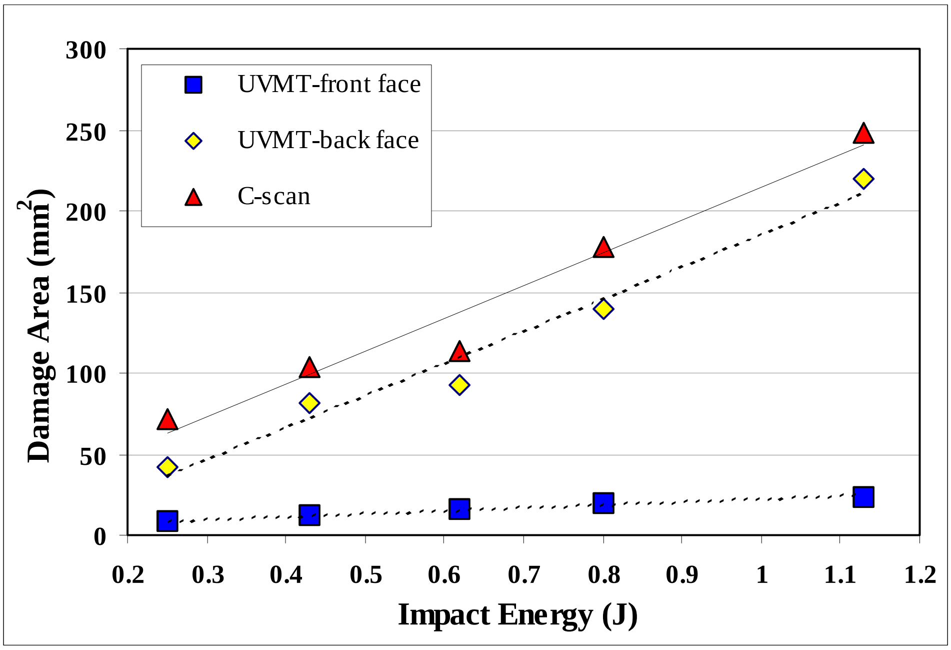


Figure 6. Correlation of damaged area measured by UVMT (from front and back faces) and ultrasonic C-scan.

4. CONCLUSIONS

A biomimetic approach has been used to develop and demonstrate a self-repairing, enhanced damage visibility, ‘bleeding’ composite which provides an effective way to recover mechanical strength and highlight concealed damage after an impact damage event .

The results of flexural testing have shown that for the lay-up investigated, a significant fraction of lost flexural strength can be restored by the self-repairing effect of a repair agent stored within hollow fibres. The ‘self-repair’ is dependent upon uncured resin (in the 0° plies) combining with the hardener (in the 90° plies) as a result of fibre fracture in both these layers. This self-repairing mechanism is not proposed as a permanent measure to eradicate the effects of damage within a composite but to provide a means to inhibit further damage propagation. The ability of self-repair has been shown to deteriorate significantly over time as the repair resin degrades. Further work is needed to optimise the repair resin used within the fibres to provide increased environmental stability and effective service life.

The release and infiltration of an UV fluorescent dye from fractured hollow fibres into damage sites within the internal structure of the composite has been successfully demonstrated. It has been correlated with respect to the ultrasonic C-scan NDT/NDE technique and shown to be an effective method of quickly and easily highlighting damage at the surface that requires further investigation. This could be of particular benefit where rapid visual inspection of large surface areas (e.g. wing skin panels) is required.

Further work is currently ongoing to refine both the self-repairing and damage enhancement processes by the use of tailored resins and dyes which provide improved repair properties, damage enhancement and environmental stability/longevity.

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FIGURES

Figure 1. Optical micrographs of fibres and composites manufactured at Bristol (a) hollow glass fibres of 60μm external diameter with a hollowness of 50% and, (b) the same fibres within a Hexcel 913 epoxy matrix

Figure 2. Lay-up configuration and dimensions for 4-point bend flexural testing.

Figure 3. Optical micrograph of cross-section through impact damaged hybrid solid glass/hollow glass/epoxy laminate.

Figure 4. Results of flexural testing for damaged, undamaged and self-repaired specimens after various storage periods (bars denote standard deviation).

Figure 5. Comparison of Ultra-Violet Mapping Technique (UMVT) viewed from (a) front and (b) back faces of specimen and (c) Ultrasonic C-scan after impact damage of 0.8J (i.e. indentation @ 1400N). (Note: images not to scale)

Figure 6. Correlation of damaged area measured by UVMT (from front and back faces) and ultrasonic C-scan.

TABLES

Table 1. Correlation of indentation load and impact energy.

Table 2. Results of four-point bend flexural testing for all specimen groups.