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Feature

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Smart restoration of internal defects in damaged composite aerostructures

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This paper presents a research project related to in-situ healing of damaged composite aero-structures. The team of five researchers was awarded a two-year technology innovation fund from Singapore's Ministry of Education to Republic Polytechnic (RP) in research collaboration with Newcastle University International Singapore from 2 May 2014 to 1 May 2016. The main objective of this research is to develop and demonstrate a rapid and effective in-situ healing technique for repairing barely visible damages (BVDs) in existing composite aerostructures.

The project focuses on a major emerging need in Singapore, namely maintenance, repair and overhaul (MRO), and has strong growth potential as identified by the Singapore government and the relevant aviation authorities. The Singapore government wants Singapore to be an aviation hub as the global aerospace industry is undergoing major changes with the use of advanced composites in commercial aircraft. More specifically, intermediate-modulus carbon fibres are widely used in the production of Boeing's Dreamliner and Airbus' A350 aircraft.

Emerging needs

Composite materials are already used in military aircraft. Hence, the project focuses on the emerging needs of various airlines and MRO companies in terms of maintenance and repair of aircraft composite structures. In addition to the aerospace industry, the repair techniques can be adapted to other industries such as automotive, marine & offshore or oil & gas, where carbon fibre-reinforced composites are in service.

The integrity loss of composite materials resulting from matrix damages caused by tool/object droppage and foreign object debris impacted at low velocity (e.g. runway stones)can be completely restored using techniques that dispense a healing medium into the damaged region. Hidden damage in aerostructures may limit the use of composites because it can affect the strength and safety of structures without the user being fully aware. The damages with the greatest concern are those that principally affect the matrix phase, involving matrix cracking and delamination between plies. Matrix cracking can initiate further damage through fatigue and provides a route for rapid moisture ingress, which can have a further deleterious effect on hot wet strength.

In-situ healing

This research work mainly focuses on in-situ healing of existing types of composite materials for aircraft structures. It draws on the successful results of self-healing, especially with regard to the reagents that can be deployed to promote healing, and the activation methods used. Carbon fibre/epoxy composite laminates were investigated because they are representative of the materials used in the main areas of concern, which include aerospace, defence and high-performance marine applications. The method developed involves penetrating and healing crack networks through the use of a fusible or curable liquid phase to penetrate and bond together the (mainly resin phase) micro-cracks and some delaminated surfaces in the composite. Matrix micro-cracks occurring in barely visible damages that penetrate the laminate surface and communicate with the rest of the damage network were investigated using a vacuum to introduce a low-viscosity liquid phase into the network of micro-cracks. Where insufficient surface-penetrating cracks occurred, strategic drilling of fine sub-critical-sized holes was investigated to permit access to this network.

Reproducible damages with a diameter of 25mm and 50mm were created in 10-ply, 16-ply, 24-ply and 32-ply carbon fibre specimens, respectively, using two thick stainless steel blocks with a centre-hole fixture. Among all the experimented healants, the Nano-Force 100 from Nano-Tech Srl has a composition of Bisphenol F Epichlorohydrin.

This healant has low viscosity properties that aid infiltration into the damaged area. Several repair methods such as dripping repair, resin injection with a vacuum chamber system and double bagging were developed to this end. Strategic drilling of vent holes in the damaged zone was experimented to study the optimum number of vent holes to achieve high repair efficiency. As the Nano-Force 100 healant was discovered later, the Epo-Tek 301 from Epoxy Technology Inc. which composition is Bisphenol A Diglycidyl Ether Resin was used to implement the various repair techniques.

Following a compression-after-impact (CAI) test, the resin injection with the vacuum chamber system repair method and 4 vent holes drilled produced the highest repair efficiency as compared to the other repair methods and numbers of vent holes. A series of specimens using the same repair mode were produced using the Nano-Force 100 healant and an average repair efficiency of 81.4% was achieved. These damaged and repaired specimens were evaluated using non-destructive testing methods such as ultrasonic C-scan flaw detection and thermography to study the crack architecture and the infiltration of the healant.

Experimental investigations

Overall, the research and experimental investigations involved quantifying the resin healing effect and repair quality through the measurement of mechanical strength properties such as tensile strength, torsional strength, flexural strength, interlaminar fracture toughness and fatigue. Experimental assessments were carried out in the laboratory under tightly regulated extreme environmental conditions, namely -57°C and 65°C, to simulate the differential temperatures experienced by the aircraft when it takes off, during cruising and when it lands.

The main benefits of the solution/product are:
- Less labour intensive as no skilled workers are required;
- Faster repair, as the proposed method can handle both the internal and external structure at the same time;
- No need to remove the "good" area, which could further damage the structure and take it further away from the objective of achieving strength recovery of the materials close to their pristine conditions.

The solution involves the development of a smart and sustainable repair technique to restore structural integrity. Specifically, this innovative technique can be used for the following types of repairs:
- Filling up cracks in the matrix material with healants;
- In case of delamination between the laminates, bonding the laminates back together with healants;
- In case of fibre fracture, bonding (only) the aligned fibre segments back together with healants;
- Repairing pulled out fibres with healants. The healant should be carefully injected into the internal cracks using a low-pressure injection technique with a specific in-house developed device.

The unique selling points and technical recommendations for this composite repair method are as follows:
- The repair can be conducted in two simple, less labour intensive stages, corresponding to the repair of internal and external damages;
- Application of healing agents into the damaged region without the assistance of a thermal source to facilitate resin flow;
- After several mechanical strength assessments, particularly CAI tests, it was found that resin injection using a vacuum chamber and the Nano-Force 100 healant was the most effective method for the repair of composite internal cracks and damages;
- An average repair efficiency of 81.5% was achieved on 16-ply composite specimens using the resin injection repair method and a vacuum chamber system, drilling 4 vent holes and injecting the Nano-Force 100 healant;
- Among all the low-viscosity healants tested, the Nano-Force 100 carbon nanotube premix allows recovering the highest compression strength in repaired prepreg samples;
- This mixed healant has an ideal density and viscosity that aid the infiltration into the damaged internal area of the composite plates;
- Special drilling steps are required to create centre holes and vent holes;
- After CAI, the composite damaged area is within 25mm from the damage centre;
- The optimum number of vent holes to achieve the highest repair efficiency is 4.

After the BVD repair, the surface repair is carried out to restore the surface back to its original condition in order to minimise unwanted aerodynamic disturbances. The innovation in the composite surface repair includes an improved resin infusion technique that uses a thin layer of low-viscosity resin injected under a thick double-sealed bag with a

Fig. 1: Vacuum chamber with resin injection system for composite repair

Fig. 2 & 3: Suction test on a composite aircraft fuselage and radome using a vacuum suction plate which will be adapted to the new vacuum chamber design

Fig. 4: NDT equipment- Ultrasonic flaw detector (Raptor) from NDT Systems, Inc

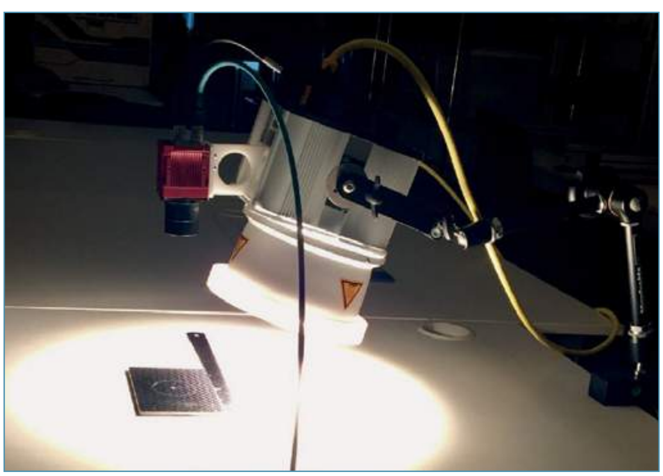

Fig. 5: NDT equipment- Infrared thermography from Automation Technology GmbH

maximum vacuum to push the resin inside the external cracks and in the remaining internal cracks, at room temperature. Following this, the standard aviation surface finishing procedure, involving a 3-layer painting process, is applied to the repaired site.

Although the research team carried out some preliminary studies for the proposed technique, the technique would clearly need rigorous in-

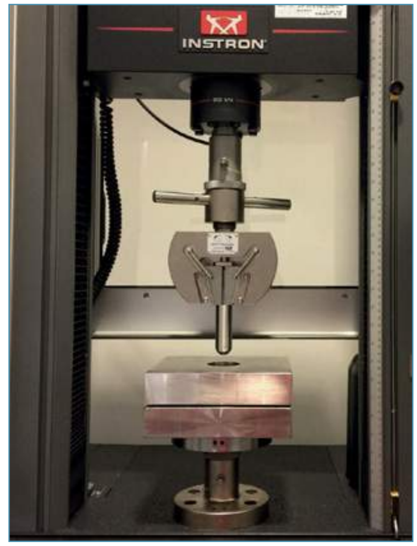

Fig. 6: Quasi-static indentation using a universal testing machine

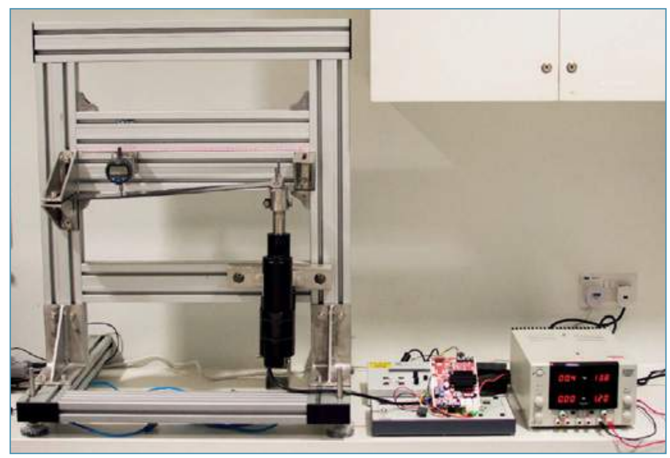

Fig. 7: Designed bending test rig for composite beams

vestigation before it may be adapted to current repair procedures for the aircraft industry, from a regulatory perspective. However, the team made good preliminary progress as the technique has already been applied to industrial-grade carbon fibre/epoxy-based prepreg composite laminates.

Overall, this internal (BVD) and external (surface) repair technique enhanced the structural strength and made the entire repair more efficient in terms of less equipment used, lower labour and repair costs, quick turnaround time for aircraft to be operational again, and easier certification and approval processes to implement repair techniques for damaged composite structures.

Awards and achievements

Dr Hamid Saeedipour from Republic Polytechnic was the principal investigator of the research project entitled "The in-situ healing of damaged composite aero-structures", which received a technology innovation fund from the Ministry of Education in collaboration with UK's Newcastle University International Singapore from May 2014 to August 2016. For his research innovation, he was conferred the Crescendas Medal & Prize for Outstanding Applied Physics Research (Polytechnics) from the Institute of Physics Singapore (IPS) on 9 February 2017. His team received JEC's Most Innovative Project Award in Aeronautics MRO at JEC Asia 2015. His final-year student team won the Polytechnic Student Research Programme (PSRP) Award 2017 in Research Programme and Best Final Year Project Status in School of Engineering. In this research field, Dr Hamid Saeedipour is currently leading three research projects on in-situ healing of internal and external damages in composite aerostructures, biocomposite green structures, and nanomagnetic particles for composite repair. He produced 12 publications and presentations on the outcomes of his composite repair research. ◻

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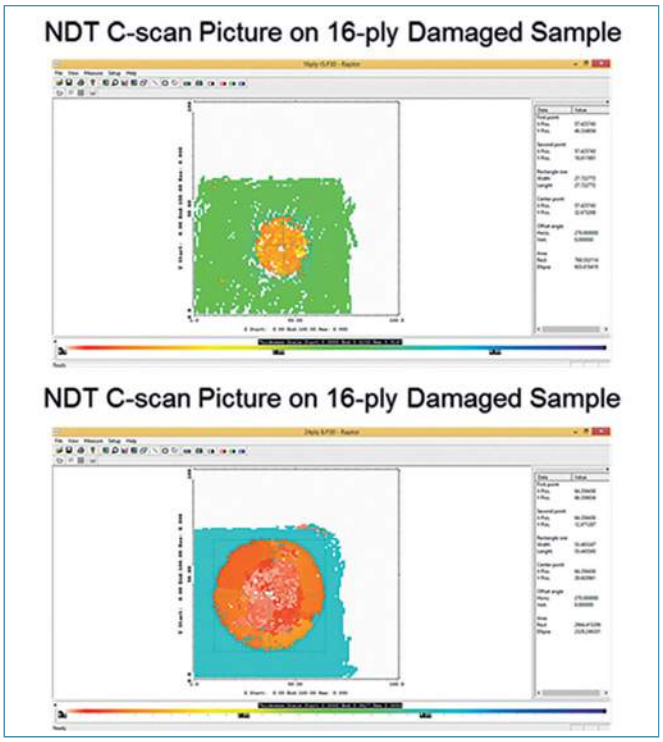


Fig. 8 : Sizes of damages in the composite laminates for 16-ply and 24-ply

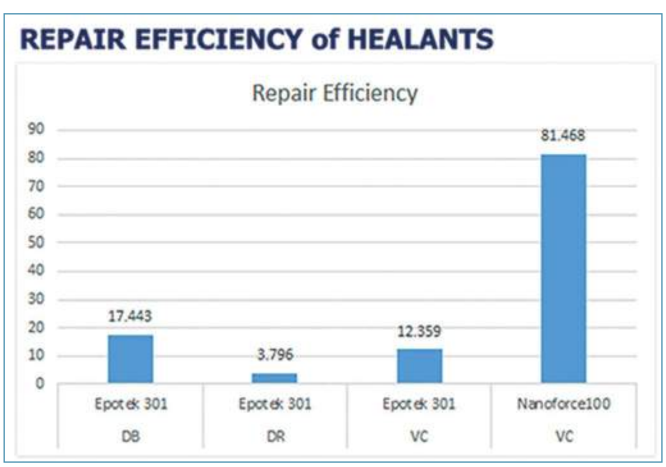
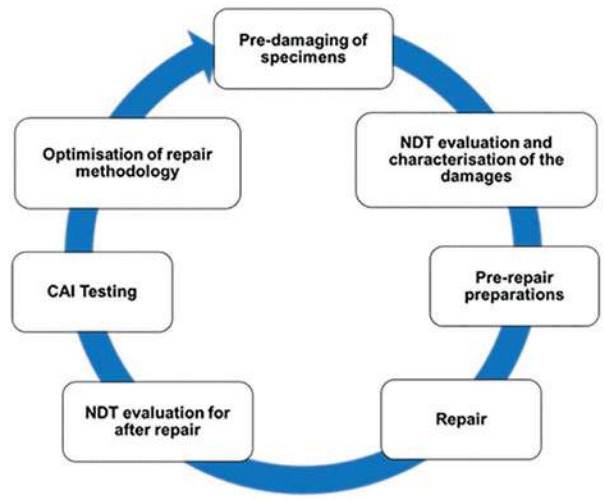


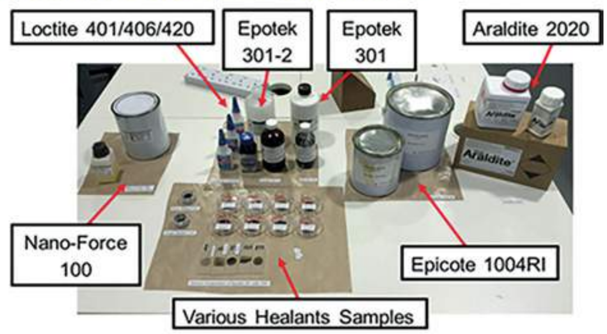
Fig. 9 : Sizes of damages in the composite laminates for 16-ply and 24-ply

Description

EXPERIMENT PROCESS FLOW



LOW VISCOUS HEALANTS USED



The portable vacuum chamber with resin injection system is intended for the first repair step, namely to repair BVDs, while the vacuum bagging system is intended for the second repair step, namely surface repair. For the BVD technique, this involves a smart diagnosis using non-destructive testing (NDT) techniques, smart drilling of fine sub-critical-sized holes to permit access to the crack network, and healing of crack networks through the use of a fusible or curable liquid phase to penetrate and fill up the micro-cracks and, in some cases, delaminated surfaces in the composite.

VACUUM CHAMBER METHOD FOR REPAIR