FOAMING SELF-HEALING AGENTS

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ABSTRACT

A new approach to self-healing systems is presented that aims to overcome the inherent drawbacks of conventional liquid resin based healing systems within composites. Finite embedded systems offer limited healing potential for small volume delaminations and as such cannot effectively heal large damage volumes often associated with shear damaged sandwich panel structures or debonding between skin and core. An expanding polymer based approach aims to overcome such limitations. The mechanical and physical properties of a prepared polyepoxide foam are investigated and how the inclusion of a carbon fibre reinforcement within the foam affects processability and performance. The healing efficiency of different polymer foams to heal damaged foam structures is also investigated.

1. INTRODUCTION

Fibre reinforced composites are becoming increasingly more prominent in both military and commercial aircraft structures due to the high specific strength and stiffness properties, low coefficient of thermal expansion and fatigue performance they exhibit compared to conventional metallic materials. However, it is difficult to detect damage on the surface of a composite laminate due to an impact load, due to the absence of a mechanism for plastic deformation. The upper plies in a laminate stack will recover elastically after an impact event whilst lower plies can delaminate and develop interply cracks. Impact events, as well as static loading and fatigue, can also lead to damage in sandwich panel structures, with foam cores often failing in shear. There has been considerable success with self-healing systems with a substantial amount of research showing that a damaged piece of composite can recover its strength almost to its undamaged state using these systems. Despite this, the vast majority of research to date has focussed on healing systems within a laminated FRP where cracks are small and the healing function is located nearby. However, it is possible to diversify the application of such self-healing approaches into sandwich structures, where damage distribution and volume are typically greater. Such a system would mitigate against potential shear damage and subsequent core/skin debonding in loaded sandwich panels.

Establishing a volume increasing self-healing system for a foam sandwich structure requires a new approach to the healing agent chemistry involved. Several factors had to be considered: the resultant post-reaction volume expansion must be rapid to avoid egress from the damaged area; the components must be stable over lengthy storage periods and still react without any retardation; expansion pressure must be
low enough to avoid exacerbating damage present but high enough to fill all voids as a result of the damage; the resulting polymer must be compatible with and adhere to the original structure. The two main classes of polymer investigated were polyurethanes and polyepoxides. Rate of expansion, density, cell size and mechanical properties of the polyurethane foams can be controlled by altering the relative amounts of reactants, blowing agents, surfactants, cross-linkers, catalysts and fillers. The investigation considered two aspects: the mechanical properties of the foams compared to conventional sandwich core polymer materials; the effectiveness of the foam system to act as a self-healing agent.

2. EXPERIMENTAL

Epoxy foams were made using a two part system consisting of a varied bisphenol diglycidyl ether and a varied polyamine hardener mixed in a 1:1 ratio. The foam was cast into a block and allowed to cure at ambient temperature for 5-6 hours before a post-cure overnight at 50°C. Epoxy foams were also cast with 1% wt. chopped carbon fibre distributed throughout the foam. Polyurethane foams were also prepared from two parts. Part A consisted solely of commercially available polymeric isocyanate. Part B contained a blend of polyols (relative amount dependant on functionality of polyol and isocyanate), n-pentane as a blowing agent, surfactant to control cell size and catalyst. Relative amounts of polyol and polymeric isocyanate were calculated based on the assumption that one alcohol group would react with one isocyanate group (in reality a slight excess of isocyanate was used to ensure complete reaction). The viscosity of Part B could be altered by varying the ratio of the polyol blend used; a higher proportion of hydroxyl terminated polybutadiene resulted in a lower viscosity premix and subsequently, a more elastomeric foam produced.

The mechanical properties of the epoxy foams were determined to ascertain their performance as a core material and provide benchmark data for healing efficiency of foaming self-healing agents. Due to the brittle nature of the foam samples, testing in axial tension was difficult due to complexities in gripping the samples and applying a uniformly distributed load. Therefore, measurement of the flexural strength of the foams was undertaken using a 4 point bend approach adapted from ASTM Standard C1161, “Standard Test Method for Flexural Strength of Advanced Ceramics at Ambient Temperature”. The support span was set at 105 mm and the loading span at 35 mm. Testing was undertaken using an Instron 3343 single column load frame with a 1KN load cell.
3. RESULTS AND DISCUSSION

There was typically significant extension with plain epoxy foam before brittle failure occurred at a mean load of 363 (±73) N. This corresponds to a mean flexural strength of 3.21 (±0.64) MPa. Addition of 1% wt. carbon fibre did not affect expansion of the foam, cure time or final foam structure. Foam samples were much stiffer with less displacement observed before failure when compared to the samples with no carbon fibre added (Fig. 1). Brittle failure occurred at a mean load of 448 (±65) N which corresponds to a mean flexural strength of 3.96 (±0.56) MPa. On average, the addition of 1% wt. carbon fibre increases the flexural strength of the epoxy foam by 23%.

Exploring the fracture surfaces of samples containing carbon fibre, it was clear that the fibres were distributed evenly throughout the thickness of the foam. On both fracture surfaces, examples could be found of fibre pull-out; holes with diameters closely corresponding to the diameter of the added fibres were observed along with fibres that were protruding from the surface (Fig. 2). We are confident that the inclusion of the fibres, through the failure mechanisms highlighted in the SEM images, are responsible for the increase in flexural strength observed.

![Figure 1: Stiffness comparison- foams with and without carbon fibre](image)

![Figure 2: (Left) Carbon fibres exposed on fracture surface of foam. (Right) Example of damage left after flexural testing. Diameter of hole is of the same magnitude as the diameter of the fibres.](image)
Fractured epoxy foam samples were used to investigate self-healing using the epoxy foam itself and a polyurethane foam healing agent. Polyurethanes offer an easier route to self-healing foams due to their lower viscosities and faster foaming/curing times compared to the polyepoxide foam systems. Healing agent was applied to the fracture surfaces of foam samples and allowed to cure before retesting. Samples cured with the polyurethane foam with high proportion of hydroxyl terminated polybutadiene exhibited the lowest average healing efficiency of 59 (±10)%. These samples also consistently failed along the original fracture surface. Samples healed with the polyurethane with lower hydroxyl terminated polybutadiene content was only marginally more viscous but resulted in a much higher and consistent healing efficiency of 97 (±5)%. These samples also failed in a different location to the original fracture line, consistently. Using the polyepoxide as a healing agent introduced drawbacks in terms of the higher viscosity and slower foaming/curing times but resulted in the highest average healing efficiency of 108 (±9)%. Again, the samples cured with polyepoxide failed in a different area to the original fracture surface when re-tested.

4. CONCLUSIONS

The aim of this study was to diversify the application of self-healing systems in composite structures and characterise and develop potential chemical systems to do so. We have shown that it is possible to deliver healing agents that will expand to fill large areas of damage in a foam structure quickly. The addition of discontinuous carbon fibre to the healing agents has shown to increase the final foam properties in terms of its stiffness and flexural strength. We can attribute this effect due to fibre pull-out in the foam during flexural testing as indicated by the SEM images taken of the fracture surfaces. We also tested different foams abilities to heal damaged foam structures and measured high healing efficiencies highlighting the plausibility of diversifying self-healing to include systems in foam core sandwich panel structures.

REFERENCES