SELF-HEALING COMPOSITE SANDWICH PANELS

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ABSTRACT

A biomimetic, vascular self-healing system, based on the infusion of a two-component epoxy healing agent, has been developed to address low-velocity, blunt impact damage to foam-cored sandwich panels. Approaches reported in previous work are applied to design a system for inclusion in specimens subject to edgewise compression tests, in which the undamaged, damaged and healed strengths are compared. Performance is reliably restored when the two-components of the healing agent are pre-mixed, and therefore ideally cured. In fully autonomous self-healing specimens, using separate resin and hardener networks, partial healing is achieved because passive mixing of the components in the damage zone produces an incomplete cure. Key improvements for the system and additional factors influencing healing efficiency have been identified for future study.

1. INTRODUCTION

Sandwich construction offers a competitive design option for advanced structures subject to bending or compression loading. High performing skin materials, especially fibre-reinforced composites, separated by a lightweight core give a structure with high bending and buckling stiffness. However, modest impact damage can have a detrimental effect on the performance of sandwich structures [1,2]. Generally, the primary damage mode for low-velocity blunt impact on a brittle-cored sandwich structure is a cohesive disbond in the core located under the impacted face with consequent loss of skin stability. Residual strengths well below 50% of the undamaged value have been reported in flexure-after-impact of beam specimens [3-5]. The loss of skin support has also been shown to reduce the compressive strength of sandwich panels by over 25% [6-10]. An alternative, bioinspired, approach from the 'traditional' damage tolerant design [e.g. 2] is to provide a material with the ability to self-heal [11,12]. This approach has been reported in pure polymers [e.g. 13-15], polymer composites [e.g. 16-18] and has recently been shown to recover failure mode and load in sandwich beams subject to flexure-after-impact [19]. In the latter case, a simple vascular network was introduced into the foam core of a composite sandwich structure. Rupture of the channels by impact damage allowed the healing agent to infuse the damage and cure. This previous study is developed in the work presented here using a more representative compression-after-impact test configuration, improved manufacturing approach and refined design techniques including a tailored network configuration.

2. SYSTEM DESIGN CONSIDERATIONS

In the previous work on self-healing sandwich panels, a beam configuration with an idealised two-dimensional damage zone was introduced [19]. This was healed using a vascular network of walled tubes bonded in the midplane of the panel with 'riser' channels through the core thickness at discrete locations. A closed, three-dimensional damage event in a panel is more representative of a practical structure, and edgewise compression has been the test of choice in most of the reported work on residual strength of practical structures. The distribution of risers in a panel can be varied in two-dimensions to give a graded density of risers, or a graded healing potential. A simple scheme for determining the spacing of the risers to ensure that damage of a given size will rupture at least one riser has been previously presented [20]. The risers must be linked by a network of supply vessels – in this case the walled tubes. How these supply vessels are interconnected and joined to the reservoirs of healing agent is driven by the need for system reliability and various configurations (e.g. branched, grid or segregated networks) are possible, depending on the specific design case [21]. The diameter of the supply vessels can also be optimised for a minimum mass given knowledge of certain variables [22]. In the case of small test specimens, the scope for optimising the supply vessel layout and diameters is limited, however the distribution of the risers offers considerable design freedom. The riser layout required for these test panels was complicated by several factors compared to the basic scheme [20]:

- Separate networks and risers are required for the two liquid components of an autonomous healing system.
- If the location of likely damage is known, it is possible to increase the riser density in this region.
- Redundancy of risers has been suggested by previous work [19, 21] resulting in an increase in riser density.
- The number of risers in the damage zone can be used to approximately meter the resin and hardener components of the healing system to the stoiciometric mix ratio.

It is clear that the design of the network, choice of healing agent and performance of the panel, both basic and post-damage, are all interlinked. These simple factors belie the possible complexity underlying the design of a fully integrated self-healing system. This makes acquiring a basic understanding of the factors involved more challenging, but does give enormous scope for tailoring and optimising the systems for different applications. This work is limited to using these ideas qualitatively to produce a simple proof-of-concept system to investigate basic functionality and mechanical performance.

3. EXPERIMENTAL METHOD

A commercially available epoxy resin system with a 2:1 mix ratio was selected as the self-healing agent. Vascular sandwich cores were manufactured from Rohacell 51IG containing 1.5mm diameter supply vessels. At strategic points, 'risers' join the supply network with the skin-core bond region to supply a zone of damage with healing agent. The channels and risers were configured to supply an anticipated damage zone of 40mm diameter from two independent networks (A & B) for the resin and hardener components respectively. The arrangement is shown schematically in Figure 1(a), which shows four resin risers and two hardener risers in the nominal damage zone. This provides riser redundancy and approximately meters the resin and hardener according to the required 2:1 mix ratio. Additional risers surrounding the damage zone provide a more realistic practical system.

Pre-impregnated $[0°,90°]_s$ unidirectional E-glass/913 epoxy facesheets (Hexcel, UK) were co-cured onto the vascular core. Samples were sectioned into specimens (60mm x 90mm) and the edges ground flat and perpendicular. The networks were filled with liquid healing agent, de-aerated and statically pressurised before impact. Damage was introduced using an Instron Dynatup 9250HV drop tower (3 Joule impact of 5.35kg drop weight, 20mm hemispherical head, rigid base). Figure 2 shows a photograph of the test configuration. The healed specimens were allowed to heal under pressure at room temperature for 48 hours after impact. Edgewise compression tests on all specimens were performed under displacement control according to ASTM C364.

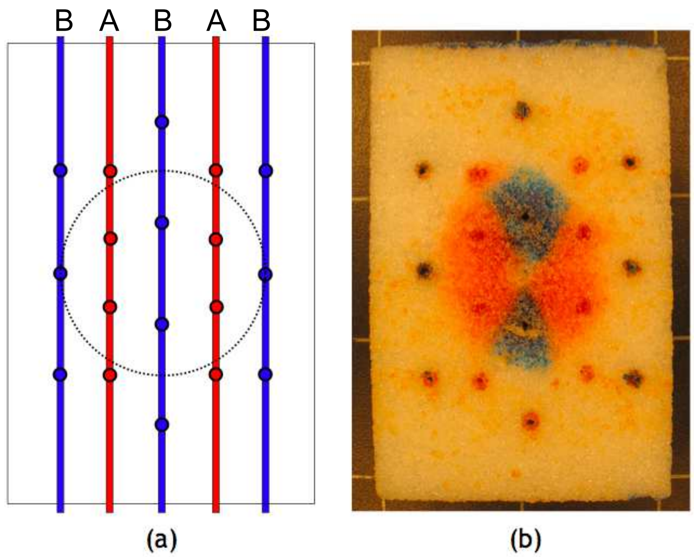

Figure 1. Healing network design and evaluation; a) schematic of riser and supply vessel layout showing two independent networks (A & B) in relation to the intended damage zone, b) foam core following impact, healing and removal of the impacted face showing infiltration by pigmented, pre-mixed resin & hardener.

Figure 2. Photograph of specimen connected to resin and hardener supplies and positioned in preparation for drop-weight impact.

Two groups of healed specimens were prepared. One group was infiltrated with the epoxy resin system pre-mixed and pigmented. In these specimens, the 'A' network was infiltrated with pre-mixed epoxy with a red pigment and the 'B' network was infiltrated with blue-pigmented pre-mixed epoxy. This group was designed to investigate the network function and healing ability, specifically to indicate the ingress of the two components into the damage zone. The healing is not fully autonomous, however this approach is a more reliable first assessment of the healing potential. Because full cure of the infiltrating resin is assured, the samples can also be destructively assessed to determine the extent to which the damage has been infiltrated from each network.

In the second, self-healed, group, the 'A' network was filled with the resin component and the 'B' network with the hardener component of the selected epoxy resin system. These specimens would asses the fully autonomous self-healing system by relying on the in-situ mixing of resin and hardener in the damage zone.

4. RESULTS

All the impacted specimens showed evidence of a subtle residual dent of roughly elliptical shape, with no visible damage to the facesheet laminate. These were measured one hour after impact and the mean dimensions are given in Table 1; there was no significant difference in the sizes across different specimen groups. The dent is slightly longer in the long axis of the specimen, coinciding with the direction with slightly greater bending stiffness due to the $[0°,90°]_s$ skin layup. Notably, the infiltration of healing agent at this pressure does not reduce the size of the residual dent.

Table 1 – Residual dent dimensions of 18 impacted specimens.

Measurement	Mean dimension (St. Dev.) mm
Major axis (0^o to specimen)	43 (±5)
Minor axis (90^o to specimen)	38 (±3)
Maximum dent depth	0.5 (±0.1)

A photograph of the damage zone of one pre-mixed specimen is shown in Figure 1(b), with the impacted skin removed, allowing the infiltration pattern of the pigmented healant to be studied. The areas of each pigmented component were measured using image analysis software (one specimen was discounted due to extensive bleeding into a manufacturing defect). The relative areas of infiltration from the different networks indicate how successfully the riser distribution can 'meter' the components of a two-part resin system close to the stoichiometic mix ratio. The ratio of the total infiltrated area to the residual dent area was also calculated. Both are presented in Table 2, which shows that the riser spacing used in this design meters the components close to the design mix ratio of 2:1. The residual dent is not, however, fully infiltrated. It has been previously determined [6] that in damage of this type, the damage void is smaller than the residual dent, and is surrounded by a region of crushed core. The evidence suggests this crushed zone has not been infiltrated with healing resin. Conversely, in all the specimens at least four resin risers and two hardener risers breached, showing that the network design, at offering a healing potential, is robust. Figure 1(b) also clearly shows negligible evidence of mixing between the flow fronts from different networks – this is a concern because autonomous healing relies on this process at the points where the resin and hardener flow fronts meet.

Table 2 – Infiltration assessment

Measurement	Minimum	Mean	Maximum
Ratio of infiltration: Network A (Red):Network B (Blue)	1.4:1	2.3:1	3.1:1
Total infiltrated area relative to residual dent.	0.48	0.67	0.77

A summary of the edgewise compression results is shown in Table 3. The impact damage reduces the failure load to 70% of the undamaged load. In specimens infiltrated with pre-mixed resin the strength was restored, and in fact increased above the value of the undamaged specimens. The self-healed specimens show modest recovery to 82% of the undamaged load. Destructive sectioning followed by visual and tactile assessment only located small areas of semi-cured resin in the zone of damage, which was mostly filled with uncured liquid.

Table 3: Results of edgewise compression tests

Specimen Group (6 replicates)	Mean Ultimate Facing Stress (St. Dev.) MPa	Relative Ultimate Stress	Most common failure mode
Undamaged	184 (±22.7)	1.00	Skin wrinkling & skin-core bond failure
Damaged	130 (±17.6)	0.70	Inward skin wrinkle at damage then overall shear buckling
Damaged & Healed with Pre-mixed resin	207 (±19.4)	1.12	Skin wrinkling & skin-core bond failure
Damaged & Autonomously Self-healed	151 (±6.55)	0.82	Inward skin wrinkle, then back face skin-core bond failure

5. ANALYSIS

A semi-empirical expression for the skin wrinkling stress of a sandwich panel was derived by Hoff & Mautner [23] and is given by:

$$\sigma_{HOFF} = 0.5\sqrt[3]{E_f E_c G_c} \tag{1}$$

where E_f is the isotropic face sheet modulus, E_c is the core modulus and G_c is the core shear modulus. Originally derived with a factor of 0.91 in front of the cubic expression; with the lower empirical factor of 0.5 it is still considered to give useful, conservative predictions for design [24, 25]. A calculation performed using the basic datasheet values for the specimens used in this work yields σ_{HOFF} = 159 MPa. All factors considered, this is in reasonable agreement with the undamaged strength of 184 MPa given in Table 3. Infiltration of pre-mixed resin into a damage zone effectively densifies the core relative to the undamaged case. To achieve the strength of the pre-mixed specimens the effective core contribution term (E_c G_c) must be increased by only around 50%. Fully cured resin would be expected to have mechanical properties many times this value. Only about two-thirds of the specimen width is 'densified' with infiltrated resin, even so this simple analysis suggests at least one other factor could be influencing the wrinkling failure. Two possible factors are the residual dent and the action of the damage as a tensile starter crack. The remaining residual dent has the capacity to significantly reduce the wrinkling load by acting as an initial wrinkle imperfection. The results also suggest that the region of crushed foam at the edge of the damage has not been infiltrated. Because the residual dent remains, the damage void is a relatively narrow zone. It has previously been shown that the wrinkle propagates as a cohesive tensile core rupture near the edge of a residual dent [6]. A more complete infiltration could have bridged any cracks remaining at the edge of the damage zone.

The low healing efficiency of the autonomously healed specimens is primarily due to incomplete cure of the healing agent resulting from a lack of active mixing in the damage zone. This is confirmed by inspection of the damage zone and supported by the evidence of the pre-mixed specimens, in which there was negligible mixing of the components from different networks. The effect of the residual dent is to narrow the damage void under the impact so the contact area between the two components is limited. That said, some healing has been achieved, sufficient to partially restore the failure mode.

6. CONCLUSIONS

This work has drawn together several studies on self-healing in sandwich structures to design and test a self-healing system for a sandwich panel. The challenge is to design a system consisting of interacting components: a conventional sandwich panel subject to a nominal design damage event, a vascular network primarily tailored for that event and an appropriate healing agent.

Functionally, the improvements over previous work allowed a robust network of tubes and risers to be constructed and showed that at the macro-scale the riser pattern can be used to meter the components into a damage zone. However, without active mixing, components only meet along a flow front so the global metering of components into a damage zone does not necessarily improve autonomous healing performance.

Mechanically, it has been shown that excellent healing efficiency can be achieved using an ideally cured resin system, even without either complete infiltration of the damage or a removal of the residual dent, providing that the properties of the cured healing agent are significantly greater than the foam core it replaces. For effective autonomous healing, it is clear that the mechanism of autonomously initiating the resin cure must be significantly improved over the passive mixing achieved here. This requires either a resin system more tolerant of the imposed cure requirements, or an improvement in healing efficiency by other means. Further work is currently underway to address these challenges.

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