DESIGN OF VASCULAR NETWORKS FOR SELF-
HEALING SANDWICH STRUCTURES

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Resistance to sub-critical damage events such as impact continues to be a concern in composite sandwich structures. Impact damage can severely degrade their flexural and compressive strengths. A self-healing system for composite sandwich structures consisting of a supply network located on the midplane of a sandwich structure core with periodically spaced vertical risers joining it to the skin-core bond region has been developed and has been shown to restore the strength and primary failure mode of impacted sandwich beams loaded in flexure.

Wider application of this self-healing mechanism presents a real and pressing need to develop a design tool or methodology that can be used to tailor the design of a healing network to meet the damage threat to a real sandwich structure in which the local loads and strengths vary over the structure. The approach uses a relationship between damage size and residual strength; i.e. for a given desired strength a critical damage size is obtained. The critical damage size is then used to define the riser spacing to ensure that an event producing damage of at least the critical size will rupture at least one vertical riser. In this way healing is initiated autonomously for critical damage. This differs from the use of these relationships to assess the criticality of damage of a known size as applied currently in the damage tolerance assessment of composite sandwich structures. A sample network is developed in a sandwich beam carrying a uniformly distributed load, showing a graded network density focused on the midspan of the beam where bending moment is highest. This study forms part of wider work that is considering both the mechanical performance of self-healing sandwich structures and optimisation of network design.

1 Introduction

Sandwich structures offer very high specific flexural stiffness by using high performing skin materials, such as glass or carbon fibre composite, separated by a lightweight core. This makes them an attractive design option in aerospace and marine applications. Reviews of the literature on impact to sandwich structures and have been performed by Abrate (1997, 1998) and Tomblin et al (1999). Early studies (Akay and Hanna 1990, Ishai and Hiel 1992, Nene and Simmonds 1992) concluded that low velocity impact damage causes damage to the impacted skin, skin-core interface and could cause a cohesive disbond in the core. Residual strengths are significantly reduced above some threshold energy and then drop asymptotically to around 50% of the initial strength, although the overall strength loss varies on a case-by-case basis. Thomson et al (1998), Mouritz & Thomson (1999) and Shipsha et al (2003) have shown that the flexural strength of foam cored sandwich structures reduces with impact induced core damage. In the latter study, flexural testing with the impact site loaded in compression drastically reduced the flexural strength to between 63% and 19% of the undamaged strength.
Three linked studies (Zenkert et al 2005, Bull and Edgren 2004, Edgren et al 2004) have been
used to develop an overall damage assessment scheme for marine sandwich structures of
different thicknesses subject to damage from a variety of impactor shapes and energies.
The scheme takes damage of a known size and generates strength reduction factors at local,
panel and global (ship) scales. These are compared to allowable reductions and the results
used to suggest appropriate remedial action.

The effect of damage on sandwich structures can be mitigated using a damage tolerant
philosophy such as that described by Tomblin and colleagues (Tomblin et al 1999). An
alternative or complementary approach is biologically inspired self-healing. Several self-
healing methodologies have been applied to composite materials to date. Solid-state healing
approaches (Chen et al 2002, 2003, Hayes et al in press) could not be expected to successfully
heal the core voids observed in impact damaged sandwich panels. Liquid based approaches
have included a microencapsulated monomer and dispersed catalyst approach (White et al
impact (Dry 1996, Bleay et al 2001, Pang and Bond 2005, Trask and Bond 2006) but both are
limited by available resin volume. Trask et al (2007) have reviewed these self-healing
approaches and self-healing in mammals and identified a biomimetic vascular network, where
the content of a reservoir are delivered to the damage site, as an advance on existing liquid
based healing approaches. A vascular network offers the advantages of addressing the larger
damage volume expected in sandwich structures, allowing multiple healing events and
allowing replenishment or renewal of the healing agent during the life of the system. Toohey
et al (2006) used an interconnected, three-dimensional grid of microchannels to distribute
healing agent throughout an epoxy polymer block to affect multiple repairs on tensile cracks
in a coating. Williams et al (2006) have integrated a simple vascular network within a
composite sandwich structure to heal cohesive failure under the impact site. A supply
network of channels 1.5mm in diameter were introduced on the midplane of a foam sandwich
core. Periodically spaced vertical risers joined the supply network to the region of bonding
with the skins, as shown schematically in Figure 1. Rupture of the risers under impact
initiated infiltration and self-healing, as confirmed with flexural testing.

![Figure 1: Three-view representation of a simple vascular sandwich structure](image)

In controlled test specimens healing vessels are placed to address a known damage location.
In a real structure the location and criticality of damage will vary due to the distribution of loads in the structure. The development of a design scheme that tailors a vascular network is key to efficient practical application.

Bejan and colleagues (Bejan et al 2006, Kim et al 2006, Wang et al 2006) have studied vascular networks for self-healing applications but have only considered healing a nominal damage size fixed through a component. In human capillaries, the branching configuration is tailored: the spacing between vessels varies from less than the vessel diameter to 10 times the vessel diameter. This is driven primarily by the need for enhanced blood supply in more active, or growing tissues (Gray 1918). This paper describes the development of a bioinspired design scheme for vascular sandwich structures which tailors the location of the vessels to grade the self-healing response in different parts of the structure. This is achieved by calculating a critical damage size for each part of the structure and grading the density of the network accordingly. To illustrate application of the method, a case study of a simple beam is also presented and the network design discussed.

2 Design methodology

2.1 Discretisation

In a generalised structure, the loading and geometry could be expected to vary significantly. It is common practice when modelling complex engineering structures to divide the components into small elements and perform analysis on each element. This is the approach suggested here, acknowledging that skill and experience will be required to select an appropriate distribution of elements. This approach could also allow interface with finite element analysis of complex structures.

2.2 Required Residual Strength Ratio

The approach adopted in this work is to calculate a critical damage size from a required residual strength ratio. It is necessary to define a strength ratio that is the minimum required to be achieved after self-healing has occurred. Firstly the allowable strength $R_{\text{allowable}}$ is defined as

$$ R_{\text{allowable}} = \frac{\sigma_{\text{design}}}{\sigma_{\text{failure, undamaged}}} \quad (1) $$

where $\sigma_{\text{design}}$ is the design stress in the element and $\sigma_{\text{failure, undamaged}}$ is the failure strength when undamaged. This ratio defines the reduction in strength that can be tolerated before self-healing is initiated and, therefore, how much of the strength loss is managed through a damage tolerant construction. An element need not be fully stressed to the design stress; those more lightly loaded will have a larger critical damage size. A local stress ratio $R_{\text{local}}$ is therefore defined as

$$ R_{\text{local}} = \frac{\sigma_{\text{local}}}{\sigma_{\text{design}}} \quad (2) $$
where $\sigma_{\text{local}}$ is the local stress on the panel element. Whilst initial studies have shown a self-healing mechanism can completely restore the flexural strength of a panel, studies on restoration of compressive strength are ongoing and so it is prudent to include a term for the healing efficiency

$$R_{\text{HE}} = \frac{\sigma_{\text{healed}}}{\sigma_{\text{failure, undamaged}}} \quad (3)$$

where $\sigma_{\text{healed}}$ is the healed strength. By using equations 1-3, the overall corrected residual strength ratio $R$ can be expressed as:

$$R = \frac{R_{\text{allowable}} R_{\text{local}}}{R_{\text{HE}}} = \frac{\sigma_{\text{local}}}{\sigma_{\text{healed}}} \quad (4)$$

The value of $R_{\text{allowable}}$ is a design decision based on the damage tolerance of the sandwich configuration chosen. The local stress ratio $R_{\text{local}}$ is determined from analytical or numerical analysis of the load and strength distribution in the structure and the healing efficiency is largely determined by the healing mechanism. The corrected residual strength ratio $R$ is a conservative ratio that can be used to produce a critical damage size at which healing will be initiated to achieve the required healed strength of the panel.

2.3 Critical damage size

Several studies have related or measured the residual strength after impact and the damage size in flexural (Thomson et al 1998, Mouritz & Thomson 1999, Shipsha et al 2003) and compressive load cases (Shipsha & Zenkert 2005, Zenkert et al 2005). These studies cover several different damage ranges using blunt and sharp impactors that produce different combinations of skin and core damage. Two studies (Thomson et al 1998, Shipsha & Zenkert 2005) have shown a threshold effect whereby the fall in residual strength is initially gradual with increasing damage size and then drops asymptotically above some threshold. A plot of damage size against residual strength ratio has conventionally been used to assess the criticality of damage of a known size (Zenkert et al 2005), conversely the residual strength ratio $R$ calculated in equation 4 can be used to determine a critical damage size for each element. Different combinations of sandwich configuration and impact type may produce a different relation between damage size and residual strength. The most appropriate approach is to produce a simple model with constants that can be altered for each configuration. One such model is given by

$$x = x_i \left( \frac{R - 1}{R_i - 1} \right) \quad \text{for} \quad R \geq R_i \quad (5)$$

$$x = \frac{A}{R + 1 - C - R_i} + x_i - B \quad \text{for} \quad R < R_i \quad (6)$$
where $x$ is the critical damage size and $A$, $B$, $C$, $R_1$ and $x_1$ are constants. Figure 2 shows this model with constants selected to fit data cross-plotted from Shipsha & Zenkert (2005) and to model a pseudo-asymptotic drop to 40% residual strength; critical damage size is plotted on the horizontal axis in keeping with the convention found in the studies referred to above. This model, or any similar relation, can therefore be used to determine a critical damage size for each element of a structure. It could not, however, be expected to produce a useful result below about $R=0.3$. The severe damage required to produce such a reduction in strength is likely to require substantial conventional repair.

![Figure 2: Critical damage size related to residual strength ratio with experimental data from Shipsha & Zenkert (2005)](image)

### 2.4 Riser spacing and diameter

In the network configuration considered in this work, it is the spacing of the vertical channels in the foam core that can be tailored to the damage state. These risers are supplied from channels located on the midplane of the core. The spacing of the risers in each element must be chosen such that damage of a critical size is guaranteed to rupture at least one channel. This means that critical damage will initiate self-healing autonomously. More closely spaced channels, while a conservative design, would cause initiation of healing for damage too small to degrade the properties below the threshold required. Channels spaced too widely risk critical damage being left unhealed. In practice this means that no point on a sandwich panel must be more than $x/2$ from a vertical riser, which is marginally, but unavoidably conservative. Initial designs have used straight, parallel supply tubes as shown in figure 1. This represents the simplest case for determining riser spacing and within this there is the freedom to tailor the spacing of the risers on adjacent channels. The arrangement shown in figure 3 meets this requirement and provides the simple design guidelines that supply channels should be laid $x/2$ apart with a distance of $x$ between risers on the same channel, with the risers on adjacent channels staggered by a distance of $x/2$. 
2.5 Scaling and integration

The stages above can be used to determine the appropriate riser spacing for each element of a self-healing sandwich structure with varying loads and strengths. In principle, each element could require different riser spacing. It is desirable that a vascular self-healing system is supplied from a limited number of pumps or reservoirs. This drives the design towards a branched, tree-like network in which the branching can be used to adjust the spacing between parallel conduits in different regions of a structure, similar to human capillaries (Gray 1918). Elegant design may require elements with similar spacing requirements to be grouped for simplicity of network design.

The placement of risers in the regions of junctions will also require further analysis. The exact details of the manufacturing process may also influence the form of the network.

3 Application

3.1 Self-healing sandwich beam

To illustrate application of the approach to practical engineering sandwich structures, a one-dimensional beam in flexure is considered. A beam with a uniformly distributed load simply supported at each end is a simple design case that can represent a variety of engineering structures, for example composite sandwich control surfaces. A simply supported beam with distributed load has a parabolic variation in bending moment with maximum moment at midspan. The upper skin will be in compression and would be expected to be sensitive to impact-induced disbonding. Assuming constant section sized for the moment at midspan, the bending stress will also vary parabolically, as will the local stress ratio $R_{\text{local}}$ as shown in figure 4. Taking nominal values for the allowable stress ratio $R_{\text{allowable}}$ and the healing efficiency $R_{\text{HE}}$ of 0.8 and 0.95 respectively, the corrected residual strength ratio $R$ is shown in figure 4. The critical damage sizes at each spanwise position are determined from these values using the relation shown in figure 3 and are plotted on the secondary vertical axis of figure 4.
These critical damage sizes have been used to define the channel spacing on a 5m x 0.5m beam, an appropriate size for an aircraft control surface. The points plotted in the main part of figure 5 show the spacing required at discrete spanwise nodes. These nodes are then connected to single supply and exit points with a branching network. The left hand half of the beam shows a configuration with the lowest integer number of branches required at each node, which results in an asymmetric network because the ratio of the number of channels in adjacent elements is not a whole number. The right hand half shows an arrangement that results in a simpler, symmetric layout at the expense of a higher channel density in some regions. The inset image shows the location of risers in one section of the network. In regions in which the supply channels run parallel this directly follows the idealised arrangement in figure 3, while in regions when the channels are converging the number of risers can be reduced. In this case inspection has been used, but more rigorous methods could be developed for use in more complex cases.
4 Discussion

The density of risers indicated on the inset of figure 5 appears large, and it is reasonable to consider how this could affect the mechanical properties of the core. It is important to note that the diameter of the risers have been exaggerated to clearly show the configuration in the figure. Determining the optimum diameter for the risers is the subject of ongoing study, but a diameter in the order of a millimetre is a reasonable estimate, meaning the total area of risers is less than 0.1% that of the core even in the region of highest density. The values used to calculate the critical damage size in this illustrative case are also estimates; the nature of a semi-empirical method such as this is that experimental data can and will be used to refine the analysis. Conservative values were used for both $R_{\text{HE}}$ and the constants in the relation plotted in figure 3. Selection of alternative values – $R_{\text{HE}} = 1$ (achieved in preliminary mechanical testing) and by selection of constants in equations 5 and 6 to match a different dataset given by Shipsha and Zenkert (2005) – give the broader spacing shown in Figure 6. In both cases the ability of the design scheme to grade the density of the network has been shown. The elements used for the one-dimensional beam case are distributed spanwise along the beam and the network density increases in the central region of higher bending moment. In a more general case, elements could be distributed in two-dimensions allowing network density grading both spanwise and widthwise for sandwich panels.

The analysis has shown the potential of the method, however further study is necessary to obtain appropriate constants for practical design. The effect of the density of a vascular network on the basic mechanical properties of a core material is also an area of potential further study.

![Figure 6: Alternative design for the inset region of figure 5 with larger critical damage size](image)

Note: Not to scale, width dimension (y-axis) and the diameter of risers enlarged for clarity

5 Concluding remarks

A bioinspired design methodology has been developed to tailor the spacing of a self-healing vascular network to the variation of critical damage size in a self-healing sandwich structure. With appropriate calibration this would allow a more efficient self-healing network in practical structures in which the local loading and strength are likely to vary. The method relies on a relationship, experimentally or analytically derived, between critical damage size and the desired strength after impact. The critical damage size may vary throughout a structure, and dividing the structure into elements has been suggested as an appropriate general method for applying the design to complex structures. The critical damage size defines the spacing and arrangement of vertical risers that supply the vulnerable skin-core bond region at discrete points.
A simple case of a sandwich beam has been used as a case study to show the tailoring of the self-healing network to the particular load state of an idealised application.

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