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Testing and simulation of mixed adhesive joints for aerospace applications

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ABSTRACT

An important aerospace application of adhesives is in heat shields, bonded with room temperature vulcanizing silicone adhesive, which has high temperature resistance but low strength. Previous works proposed mixed adhesive joints as a solution and an investigation of this technique was performed. Three adhesive joint configurations were tested, including a mixed joint. The aim of the research was to simulate the load on a heat shield and predict the joint strength. Ceramic properties were obtained with an inverse method. There was a good agreement between experimental and numerical data, showing that this technique could be used for prediction and optimization.

1. Introduction

There is significant difficulty in bonding ceramic to metals for high temperature aerospace applications. This is due to various reasons, such as the large difference in properties of the two substrates, the demanding environmental conditions and the large temperature gradients. The mixed adhesive joint technique has been proposed as a good solution for this problem and therefore its use in this application is analyzed during the course of this paper. The concept of mixed adhesive joints was first proposed in 1966 by Raphael [1]. With careful selection of the adhesives used, there is a possibility to reduce the stress concentration at the ends of the overlap, typical for single lap joints and which can reduce premature joint failure. A flexible adhesive should be present at the ends of the overlap, while a stiff adhesive is applied in the central section of the joint, where it will be less subjected to large deformations under loading. In 1973, Hart-Smith [2] recognized that the use of mixed adhesive joints could yield improvements in the mechanical strength of joints subjected to large temperature gradients. In 2007, da Silva and Adams [3] made use of this concept and predicted improvements in the mechanical behaviour of a joint under a large temperature gradient. In their approach, the adhesives to be combined were not only dissimilar in the mechanical properties, but also in their temperature handling capabilities. The stiffer adhesive was also a high temperature adhesive (HTA), responsible for the joint strength when the joint is subjected to heat while the more flexible adhesive was now a low temperature adhesive (LTA), carefully selected to be able to provide strength to the joint under negative temperatures. At higher temperatures, a high-temperature adhesive (HTA) in the middle of the joint retains the strength and transfers the entire load while a low-temperature adhesive (LTA) is the load bearing component at low-temperatures, making the HTA relatively lightly stressed. At low-temperatures, the load must essentially be supported by the LTA. If its modulus is of the same order as the modulus of the HTA, most of the load will be carried by the LTA. However, if its modulus is much lower than the modulus of the HTA, then there might still be a considerable load in the HTA. Therefore, the geometry and ratios between LTA and HTA must be carefully studied to improve the behaviour over a joint composed only of HTA. Fig. 1 illustrates the working principle of this type of joint. In 2007 [4], da Silva and Adams presented experimental data that supported these conclusions, proving the concept for a temperature range of −50 to 200 °C with titanium and CFRP adherends.

Marques et al. [5,6] performed a series of experimental studies, bonding ceramic tiles to a metallic substrate using a mixed

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adhesive joint, combining a RTV silicone with a high temperature epoxy. The joints were tested under shear at room temperature, −65 °C and 100 °C. With these static tests, mixed adhesive joints were found to have consistent strength at high and low temperature, while providing a good amount of joint displacement in both cases. Impact tests were also performed and again the mixed adhesive joint was demonstrated as a good alternative to the use of a single adhesive, able to handle large failure loads.

Cohesive zone models (CZM) are increasingly being used to improve the failure load prediction of finite element models and various authors such as Needleman [7], Tvergaard et al. [8] and Camacho et al. [9] early adapted this technique for use in adhesive joints. A CZM is able to represent the fracture process and location, advancing beyond the typical continuum mechanics modelling. It does this by including in the model a series of discontinuities modelled by cohesive elements, which use both strength and energy parameters to simulate the occurrence and advance of a fracture crack [10,11]. This technique is especially useful for adhesives, as they present a discrete zone, the adhesive layer, where failure can be expected and therefore can be easily modelled. While initially this type of element has overlapped nodes during the elastic portion of loading, when degradation of the element finally occurs the nodes start to separate and stop providing transmission of load in the model, therefore acting as a real crack in the material.

The parameters needed for the simulation can vary as well as the methods used to determine them. In this type of models there is an underlying relationship between the stresses and relative displacements of the nodes of a cohesive element. This relationship between the stresses and displacements is governed by a traction separation law, which can be shaped to better suit the behaviour of the material or interface being simulated. Fig. 2 shows such a traction separation law, where t_n *and* t_s are the yield stresses, δ_n^0 and δ_n^0 are the yield deformations and δ_n^f and δ_n^f are the deformations at failure.

The shape of this law can be changed to more adequately fit the mechanical behaviour of the simulated material. The initial elastic portion is always kept linear, but the in the literature various shapes for the softening portion of the curve can be found. Needleman introduced a shape based on more complex functions such as polynomial [7] and exponential [10] laws. Tvergaard and Hutchinson [8] suggested a trapezoidal model while Liljedhal [11] et al.

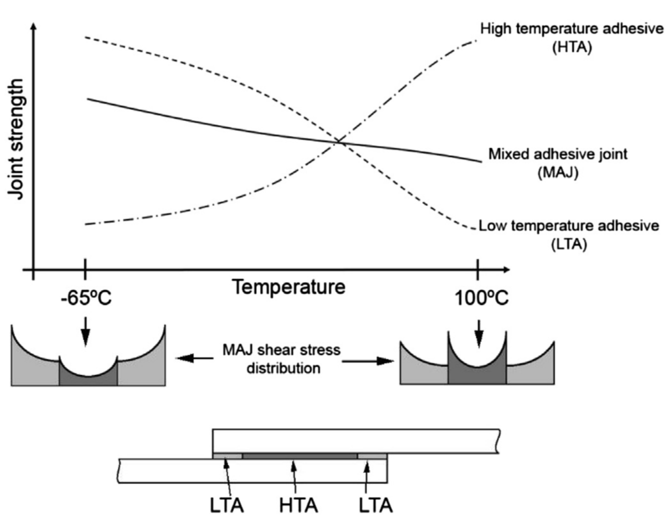

Fig. 1. Working principle of the mixed adhesive joint concept.

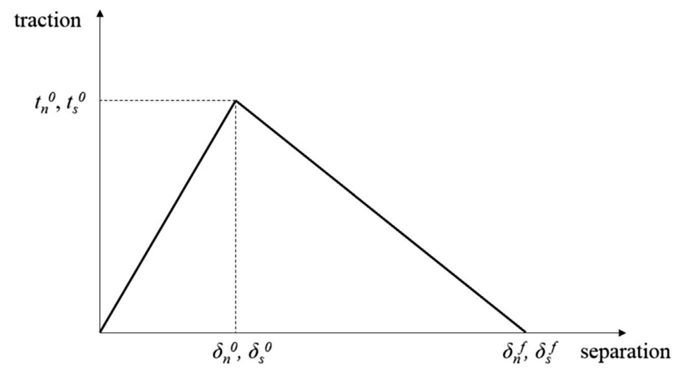

Fig. 2. Traction-separation law with linear softening.

proposed the simpler bilinear model. There is however not a consensus regarding the importance of the softening law shape. While some researchers [8,12] have determined that the shape of this portion of the law is not critical for the results accuracy, others have found the opposite effect [13–15]. Chandra et al. [15] have published a report and review of the various CZM laws available in the literature.

This work therefore aims to increase the understanding of the mixed adhesive joint capabilities, by mechanically testing metal-ceramic specimens at room temperature and under shear loading and then using this information to allow the construction and validation of a finite element model. To more accurately represent the real joint, the model makes use of cohesive elements, combining a continuum mechanics approach with a fracture mechanics approach. The cracks can therefore be simulated and matched to the cracks identified on the mechanical testing and this process leads to a validated model that can be used for joint optimization purposes.

2. Experimental details

2.1. Materials

Two different adhesives were selected, a stiff and relatively brittle high temperature epoxy of the XN1244 type, supplied by Nagase Chemtex (Osaka, Japan) and a very flexible and ductile RTV106 silicone rubber supplied by ACC Silicones LDT (Bridgewater, UK). The RTV silicone, RTV106 was selected for this experimental procedure. This type of acetoxy silicone is extensively used in high temperature applications. This one-part adhesive is known for its high temperature resistance but exhibits very little mechanical strength when compared with most structural adhesives. The curing process of the RTV106 adhesive is based in the absorption of humidity from the air [16] and, to ensure a complete cure, the water molecules must diffuse from the surface of the material to the interior. This makes the cure a slow process, especially when thick layers of adhesive are used, and 10 days are

Table 1
Mechanical properties of RTV106 silicone and XN1244 epoxy at room temperature [17–22].

	RTV106 silicone	XN1244 epoxy
E – Young's modulus (N/mm^2)	1.6	5870
G – shear modulus (N/mm^2)	0.86	2150
t_n^0 – tensile strength (N/mm^2)	2.3	68.23
t_s^0 – shear strength (N/mm^2)	1.97	37
G_n^c – mode I fracture energy (N/mm)	2.73	0.47
G_s^c – mode II fracture energy (N/mm)	5	2.2