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On the fatigue behavior of notched structural adhesives with considerations of mechanical properties and stress concentration effects

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Abstract

In this work, three types of structural modified epoxy adhesives were used to investigate the effect of stress concentrations on the fatigue behavior of notched bulk specimens. SN curves of un-notched and notched specimens were determined at constant amplitude and R = 0.1 in the range between $N_f = 10^3$ (LCF) and $N_f = 10^6$ (HCF). The following key conclusions were made: (i) fatigue strength was reduced due to the presence of notches, especially at the HCF; (ii) adhesives showed different values of notch sensitivity with values for the adhesives lower than typical values of metals; (iii) for un-notched samples fatigue strength was between 62 and 78% of tensile strength for $N_f = 10^3$ and around 50% for $N_f = 10^6$; (iv) for notched samples fatigue strength was between 67 and 78% of the tensile strength for $N_f = 10^3$ and around 40% for $N_f = 10^6$; (v) fractography evidenced the presence of voids and shear yielding around the notches, (vi) unnotched samples showed the same fracture behavior for both LCF and HCF with crack formation at the external surface. For notched samples there was a significant distinction between LCF and HCF with cracks forming at the notch root.

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Keywords: Fatigue; Stress concentration; Adhesives; Notch; Fractography; SN curve; Mechanical properties

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1. Introduction

Adhesively bonded structures are frequently used under cyclic loading conditions (*e.g*. rotating blades, engine vibration) making them sensitive to fail due to fatigue [1]. The phenomenon of fatigue, which involves the phases of crack nucleation and crack propagation, is very complex [2]. For instance, the presence of stress concentrations, *i.e*. notches, is a known factor that can severely alter the fatigue behavior of structural adhesives due to several reasons [3]:

- formation of a multi-axial state of stress;
- creation of non-uniform stress distribution;
- increase in local strain rate;

These factors combined make it difficult to accurately predict the fatigue lifetime of notched components. For this reason, designers often rely on large safety factors in order to ensure reliability of structural bonded structures against fatigue failure [4]. Since one of the driving forces for the use of structural adhesive bonding is the reduction of weight, part of this benefit is lost due to an over conservative design with subsequent cost and performance consequences [2].

Nomenclature

A1, A2, A3	types of structural adhesives
U	un-notched specimen
N	notched specimen
B	negative inverse slope of SN curve
FSL	fatigue strength loss
N_f	number of cycles to failure
k_F	fatigue notch factor
k_T	stress concentration factor
q	notch sensitivity
R	stress ratio
S_a	nominal stress amplitude
S_H	hydrostatic stress
S_{max}	maximum value of stress during a cyclic loading
S_{min}	minimum value of stress during a cyclic loading
S_o	y-intercept of SN curve
S_{VM}	von Mises stress
T	triaxiality

Since the 50's with the pioneering works of Neuber [5] and Peterson [6] several authors have dealt with the effect of notches on the stress concentrations of materials. In the case of polymeric materials Takano and Nielsen [7] investigated the stress-strain behavior of a wide range of notched polymers. They observed that polymeric materials react differently according to their mechanical properties (*e.g.* ductility). Katnam *et al.* [3] focused their work on a two-part epoxy paste adhesive. They demonstrated the formation of a stress-whitening region around the notches and that failure stress was higher with increasing triaxiality. For the case of fatigue loading, most of the available works on notch effects were focused on polymers. The main observations that can be summarized are: (i) alteration of slope of the SN curve [8,9] and (ii) reduction of fatigue performance with stronger effects at the high cycle fatigue [10–12]. Regarding structural adhesives Beber *et al.* [13] investigated the fatigue behavior of notched bulk specimens of toughened epoxies. They obtained SN curves whilst measuring the damage due to stiffness

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