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Analytical and Experimental Investigations of Extending the Crack Growth Life of Integrally Stiffened Aluminum Panels by the Use of Composite Material Strips

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Abstract: Analysis and testing of integrally stiffened aluminum panels, reinforced by carbon-epoxy or boron-epoxy bonded strips, is described. Fatigue testing was performed at room-temperature and at -50°C. The test results show a very significant increase in the crack growth life of these panels after the reinforcement. The analytical results, based on finite-element models, correlated very well with the test results.

1 Introduction

Israel Aerospace Industries (IAI) has investigated the damage-tolerance behavior of integrally stiffened metallic structures, reinforced by composite strips, as part of an international project called DaToN (Innovative Fatigue and Damage Tolerance Methods for the Application of New Structural Concepts). The DaToN project was partially funded by the European Commission (EC). IAI has performed both analytical and experimental studies of integrally stiffened metallic panels, in the framework of this EC project. This paper describes the analytical computations and fatigue testing that was performed in order to study the effect of adding composite material strips to integrally stiffened aluminum panels.

2 Testing of the Unreinforced Integrally Stiffened Panels

A total of six integrally stiffened panels were crack-growth tested under constant amplitude fatigue loading. The panels were machined from 2024-T351 aluminum alloy. The overall dimensions of the panels were a 450 mm width and a 1000 mm length. Each panel was manufactured with two integral stringers. The first three panels were crack-growth tested, without any reinforcing strips, at several stress levels and stress-ratios. Figure 1 shows a two-stringer panel in the test fixture,

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before and after failure. An artificial crack of ±15mm length was inflicted at the panel centerline. The panels had crack propagation gages bonded back-to-back to the panels, along the expected crack path, in order to monitor the crack growth. Figure 2 shows the measured results of an unreinforced panel at a maximum stress level of 80 MPa, with R = 0.1. The results shown in Figure 2 represent the mean value of the growth of the front and back, right and left crack tips. It is very clear from Figure 2 that the stringers offered almost no resistance to the advance of the fatigue crack. As such, their value as a damage-tolerance enhancer was found to be minimal. The results shown in Figure 2 were used as a baseline in order to evaluate the effect of the panel reinforcement using composite materials.

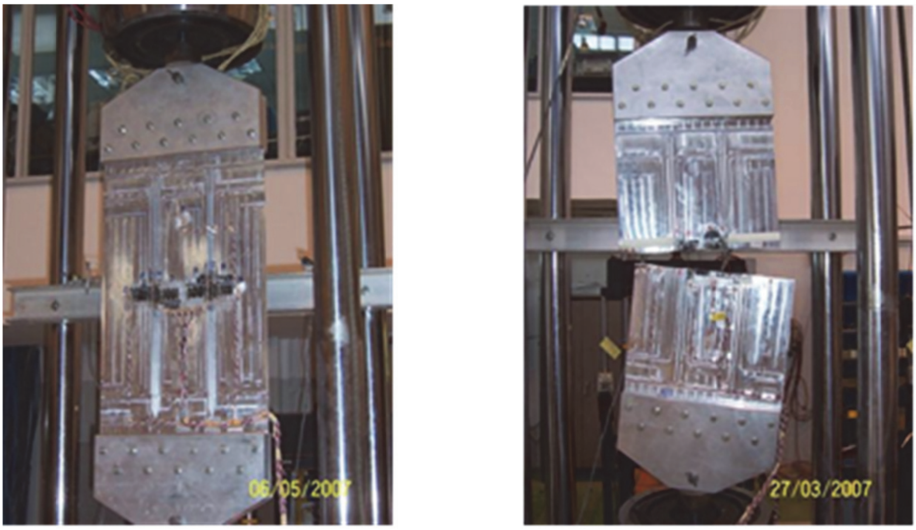

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Figure 1: A Two-Stringer Panel in the Test Rig and a Panel after Failure

3 Applying Composite Material Reinforcing Strips to the Panels

In recent years, there has been much discussion of the advantages of a "hybrid" stiffened panel which has composite materials bonded to the aluminum. The composite material reinforces the aluminum panel and serves to bridge any cracks that may develop in the aluminum panel. This bridging effect was proven during the last 30 years in many composite bounded repairs of aging aircraft [Baker et al (2002)].

In order to improve the performance of the two-stringer integral panel, two 35mm wide strips, made from Hexcel Vicotex 913 unidirectional carbon-epoxy material were co-bonded to the panels at 120°C, using 3M AF 163-2 adhesive, as is shown

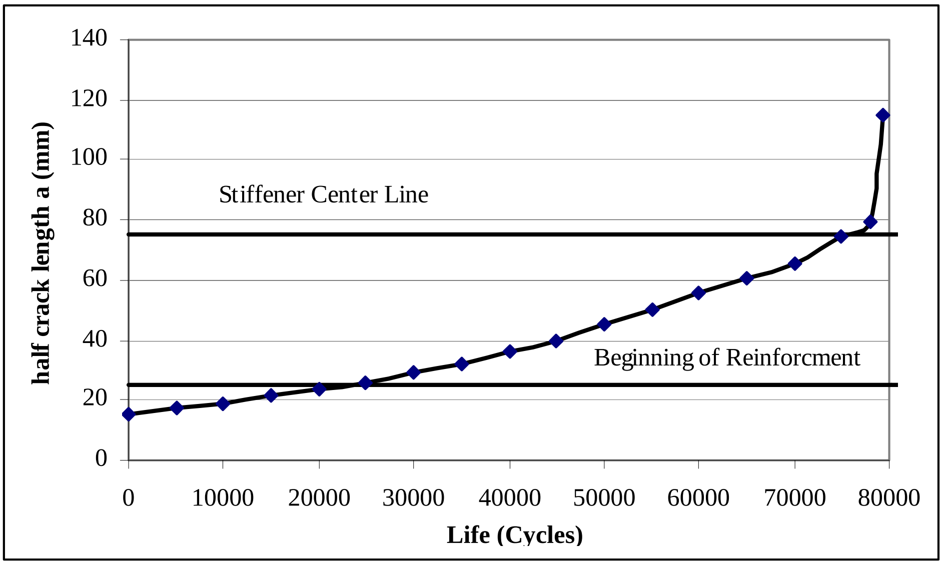

Figure 2: Measured Crack Growth Curve for the Two-Stringer Unreinforced Panel

in Figure 4. Each strip consisted of three plies of carbon-epoxy material. The purpose of the strips was to reduce the stress-intensity of a crack that grows under it, thereby increasing the crack growth life of the panel. On another identical panel, two 35 mm wide strips of Textron 5521 F/4 unidirectional boron-epoxy were bonded. Each strip consisted of two plies of boron-epoxy material. For both reinforcement schemes, the composite material strips were bonded only on the stringer side of the panels.

4 Calculating the Crack Growth Characteristics of a Reinforced Panel

A NASTRAN finite-element model (FEM) was built to study the effect of the composite material reinforcing strips on the stress-intensity factor. The model was composed of CQUAD4 shell elements representing the skin and the reinforcement strips. 3D HEXA elements were used for the adhesive. Due to symmetry, only a quarter-model was analyzed. A nonlinear analysis was performed for several crack lengths in order to examine the contribution of the composite strips on the stress-intensity values. The first step was to build the finite-element model for the unreinforced panel. The next step was to add the composite material strips and adhesive to the model. The final step was to calculate the stress-intensity of the cracked panel, for a range of crack lengths from 15mm to 100mm, using the displacementextrapolation method. The results of this stress-intensity analysis are shown in Figure 3 for the carbon-epoxy and boron-epoxy reinforced panels. It should be noted that the stress-intensity of the cracked aluminum panel is much lower at the bonding surface interface than at the free surface of the aluminum panel, as is shown in Figure 3. This means that the effect of the reinforcements is to introduce both tensile and bending effects on the aluminum panel. Figure 3 also showed a convergence of the mean stress-intensity factors to a nearly constant value beneath the strip, verifying the good agreement with the Rose Model [Baker et al (2002)] that predicts a constant stress-intensity factor under a bonded composite patch.

The reduction of the stress-intensity due to the reinforcement was taken into account by the NASTRAN analysis. The stress-intensity factors were extracted from the FEM, as a function of crack length, for the unreinforced panel, and for the panel with the reinforcing strips (at the interface between the panel and the reinforcement, and at the free surface of the panel).

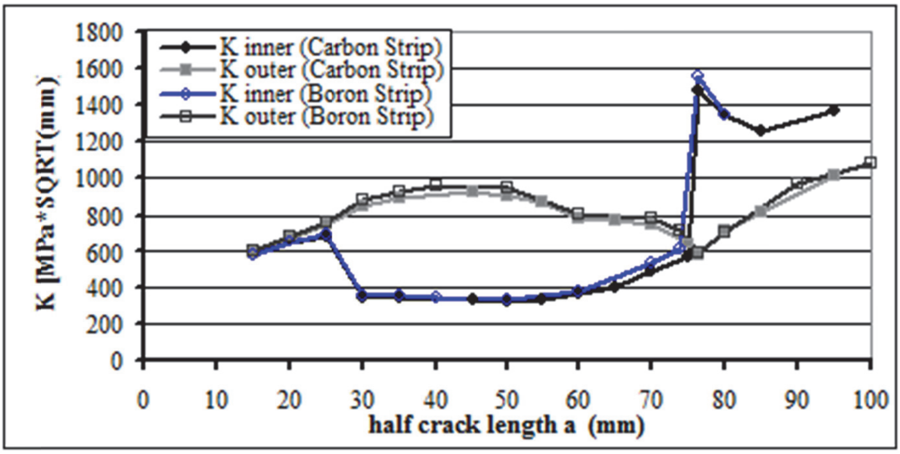

Figure 3: Stress-Intensity Results for Cracked Panels *("inner" refers to the bonding surface while "outer" refers to the free surface)*

The stress-intensity results, as obtained from the FEM, were input into NASGRO ver. 5 (crack growth software) as a data table, in order to compute the predicted crack growth characteristics. The effects of the stress-intensity variation (between the free edge and at the interface) were also accounted for by this analysis. The results of the crack growth analysis, compared to experimental results, are shown in Section 7.

5 Room Temperature Testing of the Reinforced Panels

The first two reinforced panels were fatigue tested at room temperature, under a 7% higher loading than what was used for the unreinforced panel (80 MPa at R = 0.1). The purpose of the 7% increase was to compensate for the additional EA cross-section contribution of the reinforcing strip. Figure 4 shows the reinforced panels installed in the testing fixture, before and after failure.

Figure 5 shows the crack growth test results of both reinforced panels at room-temperature. The results clearly show that both reinforced panels had a significantly slower crack growth rate than the unreinforced panel. Figure 5 also shows that the crack growth life of the three-layer carbon-epoxy strips gave somewhat better results than the two-layer boron-epoxy strips.

It should be noted that no debonds between the composite strips and the metal substrate, or delaminations between the layers, were observed up to failure for all the tested panels.

Figure 4: Panel with Carbon-Epoxy Reinforcing Strips, Before and after Failure

The crack propagation rate of all the reinforced panels seems to be constant, almost up to failure. This phenomenon is in good agreement with the Rose Model [Baker et al (2002)] that predicts a constant stress-intensity factor under a bonded composite patch.

Detrimental residual thermal stresses exist in aluminum panels reinforced by composite material patches, induced by the thermal expansion coefficient mismatch

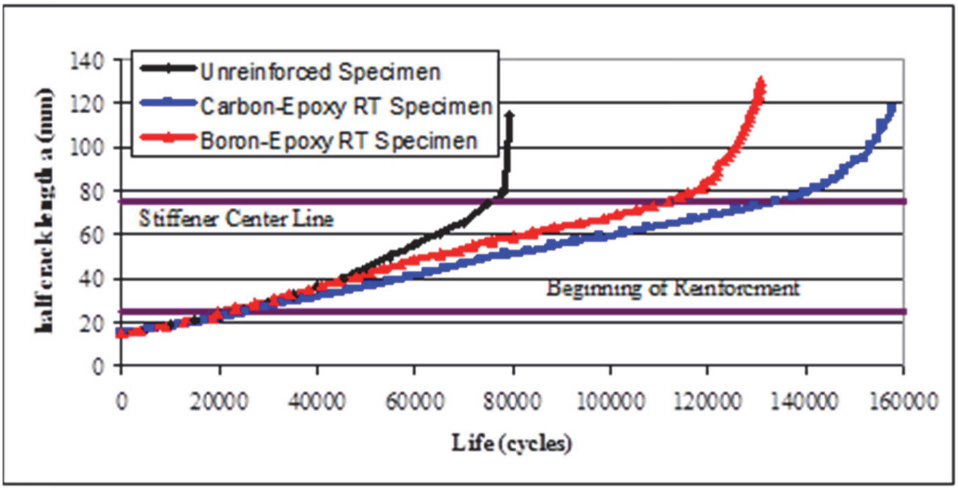

Figure 5: Comparison of the Crack Growth of Both Reinforced Panels to the Unreinforced Two-Stringer Panel. *(The loading on the reinforced panels were increased by 7% relative to the unreinforced panel.)*

between the carbon-epoxy or boron-epoxy materials and the aluminum substrate. These residual stresses may be significant because of the difference between the curing temperature 120˚C and the operating temperature. When tested at room-temperature (approximately 25˚C), finite-element studies showed that the residual stress in the aluminum panel was approximately 8 MPa for both the three-layer carbon-epoxy strips and the two-layer boron-epoxy strips, a relatively insignificant value. It should be noted that the compressive residual stress in the composite reinforcement strips was significantly higher than that of the aluminum substrate.

6 Testing a Reinforced Panel at -50˚C

The residual stress phenomenon, as described above, was shown to be more pronounced at the reduced temperatures that occur at higher altitudes. Finite-element studies showed that the residual stress in the aluminum panel will reach approximately 14 MPa for the carbon-epoxy strips at -50˚C. On the other hand, the inherent crack growth rate in the 2024-T351 aluminum panel is much slower at -50˚C than at room temperature. Therefore, an additional test was performed on a carbon-epoxy reinforced panel at an ambient temperature of -50˚C. Figure 6 shows the test setup and the refrigeration unit that was used to cool the test chamber to -50˚C. Also for this test, 7% higher loading was used, compared to what was used for the unreinforced panel (80 MPa at R = 0.1).

Figure 6: Test set-up for the Carbon-Epoxy Reinforced Panel Tested at -50˚C

Figure 7 shows that the crack grew *significantly slower at -50˚C than at room temperature*, showing that the reduced crack growth rate of aluminum at -50˚C was more decisive than the presence of tensile residual stresses.

It should be noted that, as in the previous tests performed at room temperature, no debonds between the composite strips and the metal substrate, or delaminations between the layers, were observed up to the failure.

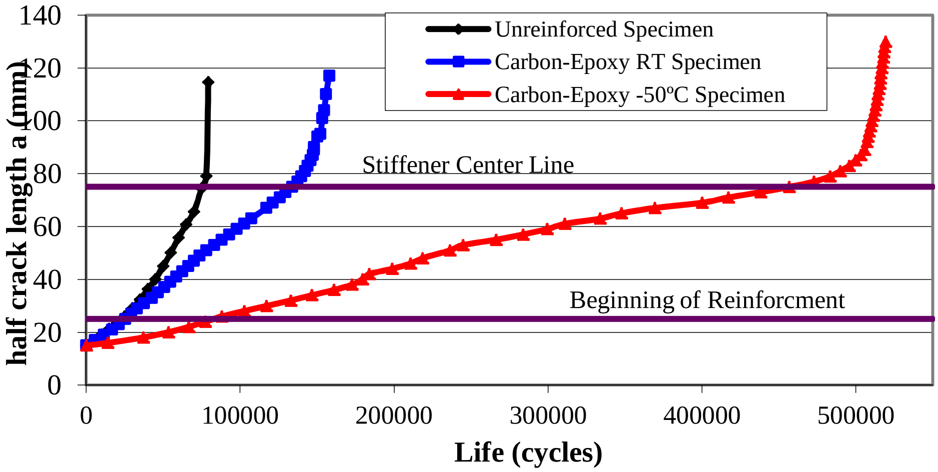

Figure 7: Comparison of Carbon-Epoxy Reinforced Panels at Room-Temperature and at -50˚C *(results are compared to an unreinforced panel*)

7 Comparison between the Analytical and Experimental Results

Figure 8 compares the measured crack growth characteristics for the carbon-epoxy reinforced panel to the analytical results computed by the methods described in Section 4. Similarly, Figure 9 compares the measured crack growth characteristics for the boron-epoxy reinforced panel to the analytical results. The results shown in both Figure 8 and Figure 9 indicate very good agreement between the test and analytical results.

8 Summary and Conclusions

This analytical and experimental study demonstrated that the use of carbon-epoxy or boron-epoxy strips will significantly increase the crack growth life of integrally stiffened aluminum panels.

Further testing and analysis is needed to *quantitatively* confirm these results.

The analytical results, derived from finite-element models, correlate very well with the test results.

The effect of tensile residual stresses in the aluminum panels at -50˚C, introduced by the coefficient of thermal expansion mismatch between the aluminum and composite materials, is not detrimental to the crack growth rate since the reduced crack growth rate of aluminum at -50˚C more than offsets the effect of the tensile residual stresses.

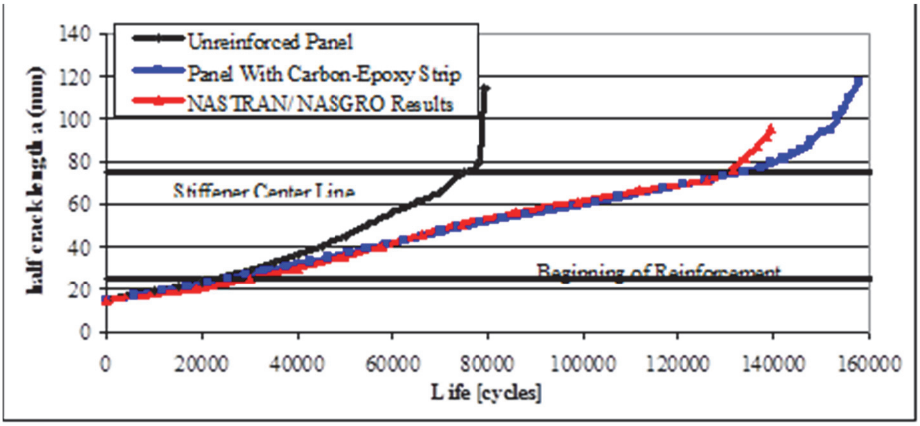

Figure 8: Crack Growth of the Carbon-Epoxy Reinforced Panel

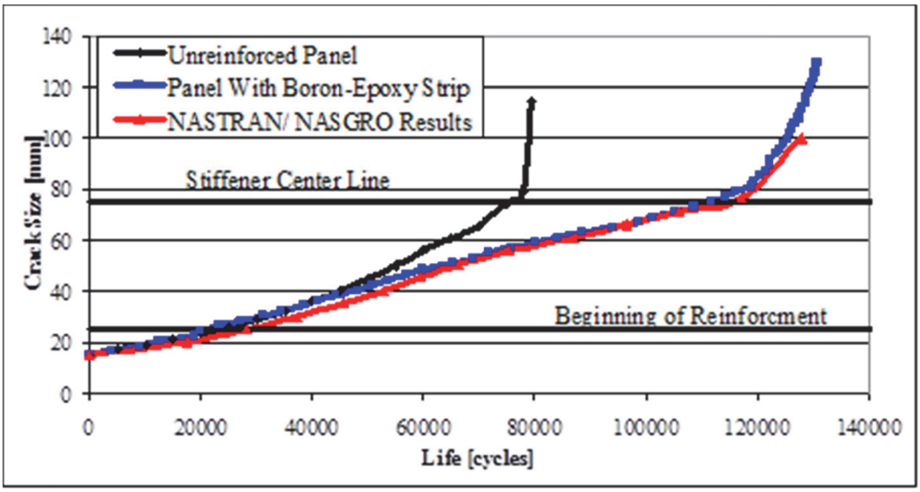

Figure 9: Crack Growth of the Boron-Epoxy Reinforced Panel

No debonds between the composite strips and the metal substrate, or delaminations between the layers, were observed up to failure for all the panels tested.

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