THE USE OF COMPOSITE MATERIAL STRIPS TO EXTEND THE DAMAGE-TOLERANCE LIFE OF INTEGRALLY STIFFENED ALUMINUM PANELS

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Abstract: This paper describes testing and analysis performed on integrally stiffened aluminum panels reinforced by carbon-epoxy or boron-epoxy bonded strips. Testing was performed at room-temperature and at -50°C. The test results identify a large potential for increasing significantly the damage-tolerance life of these panels. The analytical results, based on finite-element models, correlate very well with the test results.

INTRODUCTION

Israel Aerospace Industries (IAI) has studied 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), which was partially funded by the European Commission (EC). IAI has performed both numerical and experimental studies of integrally stiffened metallic structures, in the framework of this EC project. This paper describes testing performed under the DaToN framework, where composite material strips were used to enhance the crack growth resistance of the panels. The paper also describes the analytical calculations supporting the experimental results.
TESTING OF INTEGRALLY STIFFENED PANELS

A total of six integrally stiffened panels were crack-growth tested under constant amplitude 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 rig, 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.

In recent years, there has been much discussion of the advantages of a "hybrid" stiffened panel which has composite materials bonded to the aluminum [1] - [5]. 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 [4].

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 in
Figure 3. 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 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.

Both hybrid panels were 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 2: Measured Crack Growth Curve for the Two-Stringer Panel

Figure 3: Panel with Carbon-Epoxy Reinforcing Strips, and after Failure
Figure 4 shows the crack growth test results of both hybrid panels at room-temperature. The results clearly show that both hybrid panels had a significantly slower crack growth rate than the unreinforced panel. Figure 4 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.

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 [4] that predicts a constant stress-intensity factor under a bonded composite patch.

Detrimental residual thermal stresses exist in the aluminum panels reinforced by composite material patches, induced by the thermal expansion coefficient mismatch 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 show that the residual stress in the aluminum panel will reach 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.
This residual stress phenomenon 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 with a carbon-epoxy reinforced panel at an ambient temperature of -50°C. Figure 5 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 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 failure, for all the panels tested.

CRACK GROWTH ANALYSIS OF THE PANELS

A NASTRAN finite-element model (FEM) was built to study the effect of the composite material reinforcement 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 configurations 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 displacement-extrapolation method. The results of this stress-intensity analysis are shown in Figure 7 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 7. This means that the effect of the reinforcements is to introduce both tensile and bending effects on the aluminum panel. Figure 7 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 [4] that predicts a constant stress-intensity factor under a bonded composite patch.

Figure 7: Stress-Intensity Results for Cracked Panels ("inner" refers to the bonding surface while "outer" refers to the free surface)
The reduction at 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).

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 accounted for by this analysis. The results are shown in Figure 8 for the carbon-epoxy reinforcing strips and in Figure 9 for the boron-epoxy reinforcing strips. The results shown in Figure 8 and Figure 9 indicate a very good agreement between the test and analytical results.

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

**Figure 9: Crack Growth of the Boron-Epoxy Reinforced Panel**
SUMMARY AND CONCLUSIONS

1. This experimental and analytical study demonstrated the large potential that exists by use of carbon-epoxy or boron-epoxy patches to increase the damage-tolerance life of integrally stiffened aluminum panels.

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

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

4. The effect of tensile residual stresses in the aluminum panels at low temperatures, 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 low temperatures more than offsets the effect of the tensile residual stresses.

5. 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.

REFERENCES


