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Testing and Analysis to Understand and Prevent Jet Fighter Mid-Flight Acrylic Canopy Failures

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Abstract
Polymethylmethacrylate (PMMA) or acrylic transparencies are extensively used for commercial and military aircraft throughout the world. The sudden, mid-flight fractures of acrylic transparencies necessitated the imposition of crippling flight limitations on an entire fleet of jet fighters. This presentation will discuss the failure analysis performed on the jet fighter canopy failures including fractographic analysis, materials testing, stress analysis, and fracture mechanics assessment.

1. Introduction
The aft and forward acrylic canopies on the same jet fighter fractured mid-flight within six months of each other. Immediately after the second incident, government authorities placed 8,000-foot ceiling limitations and disallowed cockpit pressurization on all same-model jet fighters, effectively grounding the fleet. ESi performed a comprehensive failure analysis: (1) to determine the cause of the canopy fractures; (2) to recommend appropriate preventive actions; and (3) to recommend and substantiate a return to pressurized flight without altitude restrictions. Failure analysis included fractographic examination of the failed forward canopy, and comparison to laboratory-induced monotonic overload and environmental stress cracking (ESC) fractures. Chemical, thermal, mechanical, and exposure testing were also performed to determine if material degradation played a role in the failure. Stress analysis, including finite element analysis and a fracture mechanics assessment, was utilized to characterize the in-flight stresses and to estimate a critical flaw size.

2. Results
1) Fractographic analysis of the forward transparency remnants revealed the following.
   a) The overall direction of crack propagation, as evidenced by rib marks.
   b) Fracture under bending loads with the transparency inner surface under tension and the outer surface under compression. This is evidenced by compression curls on the outer surface of the transparency, and rib mark shapes consistent with cracks leading on the inner surface of the transparency.
   c) Multiple origins at the fastener holes along the periphery of the canopy, as evidenced by radial marks.
2) The fracture surfaces display no evidence of a progressive fracture mechanism (e.g., fatigue or environmental stress cracking).
   a) Laboratory-induced monotonic overload fractures resemble the service fractures. Both fractures display material stretching and a honeycomb-like appearance.
   b) Laboratory-induced environmental stress cracking fractures appear notably different than the failed canopy and the laboratory-induced monotonic overload fracture surfaces.
3) Fourier transform infrared spectroscopy, differential scanning calorimetry including oxidative induction time tests, and mechanical property testing (tensile properties, impact strength, and fracture toughness) revealed no evidence of significant material degradation due to weathering, oxidative aging, heat aging, and/or physical aging.
4) Hand calculations revealed that the Tresca stress due to cockpit pressurization is very low (<200 psi) and less than 2% of the material yield strength.
5) Finite element analysis was performed to estimate the transparency stresses at different altitudes and associated temperatures. The maximum principal stress at 35k feet (3,960 psi) is much less than the

material tensile strength (11,650 psi), but above the material craze strength in isopropyl alcohol (2,500 to 3,000 psi).

6) A fracture mechanics assessment determined that the critical crack or flaw size is on the order of 0.12" (3mm).

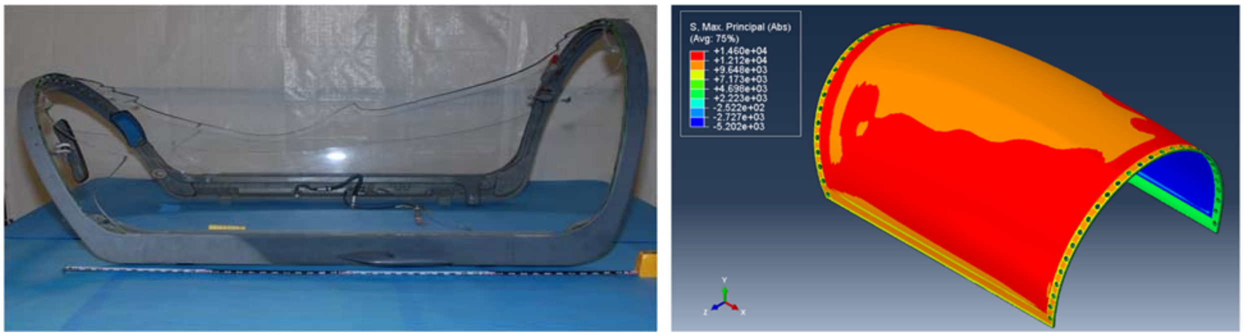

Fig.1 – Images showing the failed forward canopy and FEA results at 35,000 feet altitude.

3. Conclusions

1) The cause of the two canopy failures appears to be isolated to a single aircraft, because: (A) failure did not occur early in the service life; (B) transparency failures have not occurred in other similar aircrafts; (C) evidence of one of the progressive, time-dependent failure mechanisms (i.e., material degradation, environmental stress cracking, and/or fatigue) is absent; and (D) the predicted nominal stresses are low. This suggests that the subject aircraft canopies were exposed to an unusual event and that the evidence of this event/failure mechanism was lost with the missing/un-retrieved transparency fragments. Purportedly, hydraulic fluid had contacted the transparencies. Isopropyl alcohol is readily available and may have been used for cleanup after the hydraulic fluid exposure.
2) The effect of pressurizing the cockpit to 4 psi has a negligible effect on the transparency stresses and poses little or no added risk.
3) The effect of altitude or temperature on the transparency stresses is greater than the effect of pressure. However, if appropriate measures are taken to preclude canopy exposure to stress cracking agents, the additional risk is low at 35k feet (3,960 psi) versus 8k feet (1,244 psi).
4) The most likely failure scenario is the existence of crack-like defects combined with the decrease in fracture toughness due to low temperature (high altitudes) and/or exposure to detrimental chemicals (i.e., stress cracking agents).
5) It is imperative that periodic nondestructive testing procedures are in place to assure that no cracks greater than approximately 1mm exist and that the transparencies are not exposed to detrimental chemicals. It is noted that current procedures can detect microcracks at an appropriate size (0.1mm), an order of magnitude less than the estimated critical crack size.

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