PROPAGATION OF 'POPCORN' FAILURE IN COMPOSITE PLATES BY MODE I DELAMINATION UNDER THE COMBINED EFFECT OF NON-UNIFORM HEATING AND ABSORBED MOISTURE

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During their service exposure, composite structures may be subjected to local heating under which three dimensional temperature gradients may develop with temperature differences that can exceed 150°C. The differential thermal expansion that is associated with such temperature gradients can generate a range of thermal stresses. An example that was studied recently is one of spot heating of the outer surface of a composite plate, generating compressive thermal stresses around the periphery of the heated zone, leading potentially to delamination by buckling. It was also found that a threshold level of moisture is a prerequisite for the occurrence of such delamination.

Following those observations we studied the combined effects of non-uniform heating (Figure 1) and moisture in glass and carbon fiber reinforced epoxy composite laminates [1]. The main observation was that delamination damage in a form of bulge occurs only in the presence of absorbed moisture. In fact only in the presence of a threshold level of moisture of about 1 wt% does non-uniform heating cause bulging. This threshold level corresponds to the critical moisture content found to produce major mechanical property reduction and inter-lamina separation.

Finite element analysis showed that non-uniform heating per se does not account for the mechanism of bulging as the in plane and normal stresses that it generates are too small to cause either buckling or delamination, respectively. Instead, the proposed mechanism comprises a chain of consequences induced by moisture, wherein chemical degradation of the inter-lamina hot region is followed by mechanical inter-lamina separation and bulging caused by steam pressure [2].

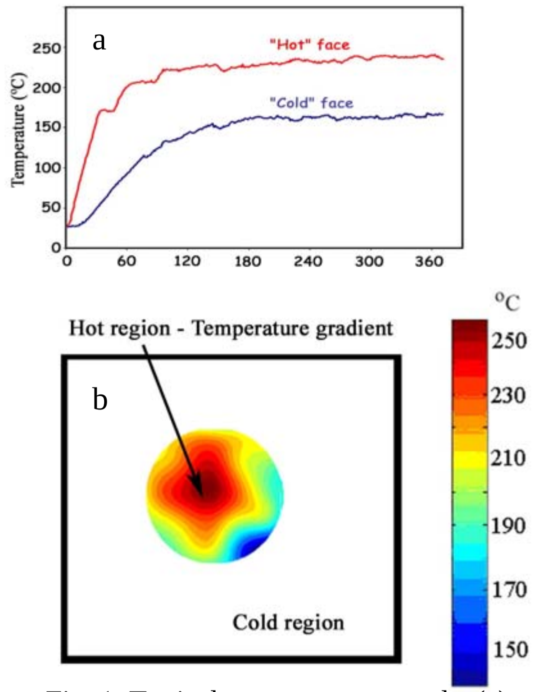

Fig. 1. Typical temperature records: (a) temperature-time profile in the center points of the upper ("hot") and lower ("cold") faces; (b) in-plane temperature profile of the "hot" spot.

Spot heating of a 'wet' laminated composite plate produces a bulge shaped delamination (Figure 2), categorized as 'popcorn' delamination. It is created by internal pressure due to nascent steam pockets generated by the intense heat. The mechanism of crack propagation from a ‘penny shaped’ bulge to broad delamination is analyzed. Finite element modeling, based on the condition that the crack propagation occurs by Mode I delamination (Figure 3), is utilized to obtain the ratio of stress intensity factor to internal pressure as a function of the growing crack radius. This is then used to evaluate the critical pressure that triggers crack propagation. Assuming that the bulge is shaped like a spherical cap, the volume and the internal pressure can be estimated for any particular delamination crack radius [3]. Finally, the critical moisture content required to generate a 'popcorn' bulge can be calculated as a function of the diameter of an initial 'penny shaped' crack (Figure 4). If the equilibrium moisture content of epoxy composite materials during service exceeds this value, the 'popcorning' mode of failure may occur with non-uniform heating.

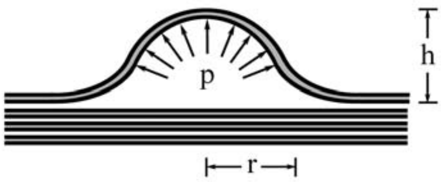

Fig. 2. A schematic presentation of a bulge formed under the effect of uniform pressure *p*.

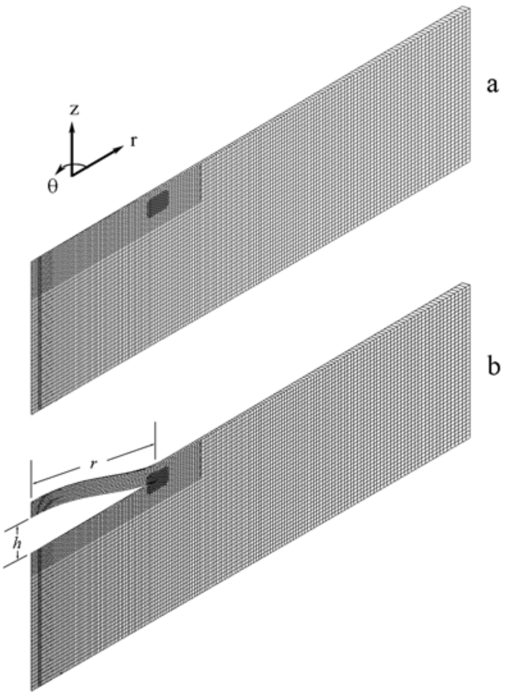

Fig. 3. Finite element model for a wedge shaped segment of the bulge, showing: (a) the pre-delamination state and the designated coordinate system; and (b) the crack opening mode configuration, including the 'process zone' at the tip of the crack and marking the crack length (*r*) and opening displacement, COD (*h*).

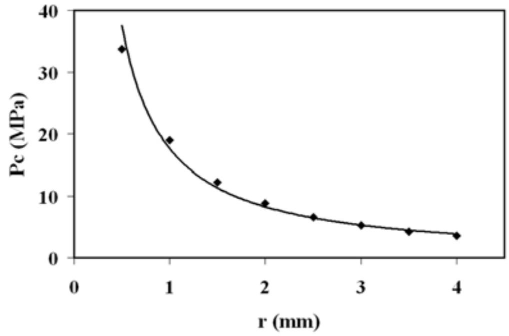

Fig. 4. The critical pressure (p_c) as a function of the crack radius (*r*).

The paper will present in detail the results of the effect of moisture on the mechanical properties, the simulation experiments of non-uniform heating including in-situ measurements of temperatures and strains, the finite element model used to calculate the resulting mechanical stresses and a schematic model of the observed delamination by bulging.

References

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