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Thermally Induced Stresses Due to Coefficient of Thermal Expansion Mismatch in Hybrid Metallic/Composite Structures

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16\. Abstract

The issue of thermally induced stresses due to a mismatch of the coefficients of thermal expansion (CTEs) between two or more components in a joint has implications not only for structural assemblies comprised of different metallic alloys but also hybrid composite and metallic structural assemblies. The pertinent structural analysis requires the contribution of thermally induced stresses to the mechanically induced stresses of a joint subjected to a heat flux and thermal strains from a resulting temperature gradient.

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TABLE OF CONTENTS

LIST OF ACRONYMS

CTE	Coefficient of thermal expansion

EXECUTIVE SUMMARY

The issue of thermally induced stresses due to a mismatch of the coefficients of thermal expansion (CTEs) between two or more components in a joint has implications not only for structural assemblies comprised of different metallic alloys but also hybrid composite and metallic structural assemblies. The pertinent structural analysis must consider the contribution of thermally induced stresses of a joint subjected to a heat flux and thermal strains from a resulting temperature gradient in addition to the mechanically induced stresses.

THERMALLY INDUCED STRESSES DUE TO COEFFICIENT OF THERMAL EXPANSION MISMATCH IN HYBRID METALLIC/COMPOSITE STRUCTURES

Thermally induced stresses due to a mismatch of the coefficients of thermal expansion (CTEs) between two or more components in a joint have implications on structural assemblies comprised of different metallic alloys and hybrid composite and metallic structural assemblies. The appropriate structural analysis requires the contribution of thermally induced stresses of a joint subjected to heat flux and thermal strains from a resulting temperature change be combined with the mechanically induced stresses. The superposition of thermal stresses in linear combination with mechanically induced stresses is supported by classical theory of elasticity, which forms the basis for thermal loads development through computational finite element methods [1].

Thermally induced stresses develop as the result of global heating and cooling of the aircraft structure from hot/cold ground-soak conditions and hot/cold flight-maneuver conditions. Global thermal loading effects are due to a mismatch of the CTE between connected components and require determination of the global structural response under thermal conditions (e.g., a mechanical joint between a graphite/epoxy skin and an aluminum frame/stringer). Thermal stresses develop when the CTE between the metallic and composite parts fastened/bonded together are substantially different, and the joint is subjected to a temperature differential between the temperature at the time the assembly was put together and the current operating temperature, which can cause expansion or contraction of the joint. For example, a hybrid assembly was manufactured at a room temperature of approximately 75^{o} F. After the aircraft takes off and cruises at 35,000 feet above sea level, the ambient temperature is approximately -65^{o} F. Because of this 140^{o}F temperature differential, the aluminum frame/stringer that typically has a higher CTE than the composite will try to contract much more than the composite skin. However, the composite skin will prevent the aluminum frame/stringer from contracting as much as it would. This gives rise to thermally induced tensile stresses in the aluminum part and compressive stresses in the composite skin due to the mismatch of CTE.

Thermally induced stresses could also be generated as the result of local heating and cooling effects caused by the operation of systems within the aircraft (e.g., heat exchanger, auxiliary power unit, etc.). When such a structure subjected to local heating or cooling effects is attached between other rigid structures that could prevent the expansion or contraction of the part, high thermally induced loads can develop. A similar situation arises when a temperature gradient develops over a portion of the structure, resulting in localized, thermally induced loads caused by the restraining effects of the surrounding material within the part not subjected to the heat source.

Several parametric studies were conducted to experimentally investigate thermally induced stresses in fastened hybrid structures of aluminum and composite constituents and to develop an analytical model to simulate the physical system and predict the thermally induced loads. These studies also included the effects of the length of the hybrid joint on the thermally induced stresses.

Part of the experimental investigation was to take strain gauge readings of the hybrid joint during the test to extract the contribution of the thermally induced stresses. The strain readings ($\boldsymbol{\varepsilon}$) will have two components: temperature output $\boldsymbol{\varepsilon_{T0}}$ (i.e., the output of the strain gauge due to the change in internal electric resistance of the gauge resulting from the change in temperature) and the actual deformation of the strain gauge. The temperature output ε_{T0} component of the total strain reading is usually given by the gauge manufacturer in the form of a cubic polynomial that is a function of the temperature at the instance when the strain data were recorded. The second component of the total strain reading, namely the actual deformation, is comprised of two parts: thermal strain $\boldsymbol{\varepsilon_T}$ due to thermal expansion/contraction, and mechanical strain $\boldsymbol{\varepsilon_M}$ due to mechanically induced tensile/compressive stress. The thermal strain $\boldsymbol{\varepsilon_T}$ is typically given by the following formula:

$$\varepsilon_T = \alpha(T - T_0) \tag{1}$$

where $\boldsymbol{\alpha}$ is the CTE of the aluminum frame/stringer and T_0 is the initial temperature. Therefore, the mechanical strain in the aluminum frame/stringer was obtained from the strain reading by subtracting the temperature output and thermal strain contributions [2]:

$$\varepsilon_M = \epsilon - \epsilon_{T0} - \varepsilon_T \tag{2}$$

The studies to investigate the effect of length of the hybrid joint on the thermally induced stresses showed that for all tested cases of various fastened lengths, the peak strain (and stress) of the aluminum frame/stringer always occurred around the center of the fastened assembly because of the gradual buildup of strains from the ends of the joint. The peak strain increased with longer joints and reached a plateau after the fastened length reached a certain value. Conversely, the study showed that the peak fastener load transfer occurred at the end fasteners, whereas the fasteners at the center carried very little load. Similar to the peak-strain behavior, the peak-fastener load transfer reached a plateau after a certain fastened length of the joint, which may be different from the length at which the peak strain reaches its plateau.

The above thermal-stress consideration should be given when designing a structural modification that affects a hybrid metallic/composite structure. The design of the modification should be optimized to reduce the generation of thermally induced stresses that could affect the fatigue performance of either metallic or composite constituents of the joint.

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