

Continuous Maintenance of Damaged Aircraft Wings: A Comprehensive Review

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Introduction

Continuous maintenance is necessary for ensuring structural integrity of an aircraft. Damage to structural components in aircraft could be caused by corrosion, stresses, fracture and erosion. Inspection performed to locate these damages includes shape of repair stripes to use in order to fill the damage; the type, size, and number of rivets needed; and the strength, thickness, and the kind of material required. Traditional repair is done by installing splice members using bolts or rivets on the damaged area. These spliced members are usually one gauge heavier or made of the same material at the least. This will ensure that the part will get back to its original structural capacity. Hence, the selection of material and adhesive for the sections becomes important. Parameters like shape and size of the stripe, number of plies, their stacking sequence, selection of adhesive material (epoxy, BMI, etc.) and its thickness are key to this process.

Repair of Wings by Composite Stripes

Over past few years, composite stripe repair has gained popularity [1]. Some of the advantages are:

- No fastener holes for stripe application and hence no possibility for micro-cracks to develop
- The section is bonded to the structure leading to uniform stress field
- No drilling is necessary
- Ease of stripe application
- Uniform stress transfer results
- Reduced stress concentrations

The use of bonded composite stripes to repair damaged aircraft and marine structures has been first studied by Baker [2]. Baker et al. [3] detailed the advances in the field of bonded composite repair till the year 2003. Mathias et al. [4] Provided some solutions for the stress distribution in rectangular composite stripes under in-plane loading both normal and shear stresses. Interlaminar stresses of a laminated composite stripe using an ESL model under a bending load was investigated by Lee et al. [5] using Lekhnitskii stress functions. Several methods for stress analysis [1, 5-15] are available in literature. Most of these methods discuss the use of finite element methods to analyze stresses which are interlaminar and at the adhesive plate interfaces. Benyahia et al. [6] showed that the fatigue life of cracked plates was increased fifteen times by one-sided composite striping. Beghini et al. [8] studied the performance of the bonded composite reinforcement or repair for reducing stress concentration at a semi-circular lateral notch and repairing cracks emanating from this kind of notch. They highlighted the effects of the adhesive properties on the variation of the stress intensity factor at the crack tip.

Rachid et al. [10] analyzed the effects of the stripe shape on the efficiency and the durability of bonded composite repairs of aircraft structures. Albedah et al. [13] estimated the performance of the bonded composite repair of metallic cracked aircraft structures by analyzing the J integral and the plastic zone size around the crack tips for single and double symmetric stripes. Albedah et al. [14] analyzed the effect of the thermal residual stresses resulting from adhesive curing on the performances of the bonded composite repair in aircraft structures. Calculation of stress intensity factors [16-19] to analyze fatigue behavior is to be performed whenever the model is subjected to cyclic loading conditions. Several researchers [20-24] have published numerical and experimental studies to analyze the fatigue behavior.

Iso-geometric Analysis (IGA)[25] approach is a modern numerical method used to model composite repair. IGA could be used to integrate numerical analysis into Computer Aided Design (CAD) tools and vice versa. This will ensure that the exact geometry of the repair stripe will be always maintained, which does not happen when iso-parametric elements are used in traditional FEM. This method has also an advantage of easy implementation of refinement techniques. Maintaining the exact geometry will enable us to model non-primitive shapes for repair stripes without the necessity of subsequent communication with a CAD (Computer Aided Design) description. IGA will use NURBS (Non-Uniform Rational B-Splines) basis functions to create the exact geometry and to construct finite approximations for analysis [26].

Thermal Survey and application to Repair

A thermal survey is performed prior to installing the repair to ensure proper and uniform temperatures can be achieved. The thermal survey determines the heating and insulation requirements, as well as thermocouple locations for the repair area. The thermal survey is especially useful for determining the methods of heating (hot air modules, heat lamps, heat blanket method and monitoring requirements in cases where heat sinks (substructure for instance) exist in the repair area.

Thermal variations in the repair area are caused due to different reasons. Variation in the heater blanket's thermal pattern, as well as repair structure heat sinks, will set up a varying thermal profile. Other most important contributors are the material type, material thickness, and the underlying structure in the repair zone. Thin skins heat quickly and can easily become overheated whereas the thick skin sections absorb heat slowly and take longer to reach the soak temperature [27]. A thermal survey identifies these problem areas and allows the repair professional to develop the heat and insulation setup required for even heating of the repair area.

Traditionally, a thermal survey is conducted by attaching a stripe (called a *surrogate stripe*) of the same material and thickness, several thermo-couples, a heating blanket, and a vacuum bag to the repair area. The area is heated until the temperature becomes stabilized and is recorded using a thermocouple. This process is primarily done to identify both the hot and cold areas in the repair zone. Some areas, like the one with stringers and ribs, might have a lower temperature than the area in the middle of the stripe and start to act as heat sinks. These regions would need insulation to increase the temperature to make the profile more uniform.

The numerical methods [28-30] such as the finite element method and the finite difference method are widely used in solving complex problems related to thermal effects with the help of commercial software such as ANSYS, ABAQUS, and MSC NASTRAN. Devarajan et al. [31] used ANSYS to analyze the response of a bolted joint under a model thermo-mechanical load. Kapania et al. [32] used a three-noded triangular flat shell element, termed AT/DKT, for free vibration, linear thermal/piezoelectric, and geometrically nonlinear analysis like snap-back, snap-through, thermal post-buckling, dynamic buckling, and the follower effects of the pressure loads. The element was first applied to study the control of thermal deformations of a spherical mirror segment [33]. This kind of study was required for the design of a next-generation space telescope that employed a multi-segmented primary mirror. The feasibility of controlling the surface distortions of the mirror due to arbitrary thermal fields, using piezoelectric strips and force control actuators was studied using a finite element model of the mirror. Other researchers have used the same element for performing thermoviscoelastic analysis of composite structures [34].

Conventional thermal surveying techniques entail the construction of a conventional surrogate stripe. This is a time-consuming and labor-intensive process and typically requires hand-cutting of multiple composite plies each having a unique size and shape for each repair or rework area. Furthermore, the conventional practice of performing the thermal survey and drying cycle as two separate processes result in the application of two heating cycles on the composite structure which may affect the service life. Furthermore, the conventional thermal survey requires the labor-intensive and time-consuming process of fabricating the conventional surrogate stripe after which the surrogate stripe is discarded following a single use.

Heat transfer in the repair areas is governed by three factors conduction through the material, convection from the surface, and radiative heat exchange between different parts exposed to the environment. The repair area should mesh in such a way that the nodes are located at places that possibly would have had a thermocouple attached. Natural convection should be assumed on the skin surfaces. The region should be meshed using linear hexahedral and wedge heat transfer elements with linear interpolation.

Heating of the surrogate stripe can be achieved by inputting a heat flux that will be equivalent to the heat provided by the heat blanket and performing a transient uncoupled heat transfer analysis till the steady state is reached. Temperature versus time plots at the nodes where the thermocouples would have been placed could be generated and compared against existing experimental data for validation. This method for performing a thermal survey could obviate the need for fabricating a duplicate of the final stripe for determining the temperature profile in the repaired region. The result will be a thermal map of the repair area.

Optimization Methodology and Sensor Placement

Evaluating thermal maps to determine the optimal location of thermal sensors has been researched for many years [35, 36]. Memik et al. [37] presents observations on thermal maps and points to opportunities for making an informed decision on sensor placement. It introduced a thermal sensor placement on the Intel Pentium 4 microprocessor. By analyzing extracted thermal maps, they found optimized locations of the thermal sensors by identifying common

hotspots. A thermal map was extracted by observing the thermal behaviors of popular applications. The works concerning thermal map reconstruction via optimized sensor placement can be found in more specific areas such as microprocessors [37]. D'Antona et al. [38] used the metaheuristic algorithm called Genetic Algorithm [39, 40] to select a proper set of locations to place thermal sensors which lessened the trade-off between stability and resolution of the temperature data. The sensor positioning and choice of the number of sensors were optimized in terms of the reconstruction of the temperature field considering the error propagation in case of uncertain measurements using a genetic algorithm.

Over the years, the De et al. has performed significant work using metaheuristic algorithms like Genetic Algorithm and Particle Swarm Algorithms for solving large scale optimization problems [41-52]. The large-scale optimization problem of optimal placement of a large number of piezoelectric actuators [53-57] on the adaptive structures were solved by using the method of combined finite element analysis and genetic algorithms. The sensor placement problem is greatly related to the actuator placement problem.

Devarajan et al. [58-66] recently worked on developing computationally efficient models for composite structures using iso-geometric analysis which could be used to accelerate optimization process.

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