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OPTIMAL DESIGN OF A COMPOSITE SCARF REPAIR PATCH UNDER TENSILE LOADING

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ABSTRACT

Mechanics of the composite scarf repair under tensile loading with and without overlay plies was examined for nontraditional patch ply orientations. Three-dimensional nonlinear analysis was performed for repair failure prediction and good baseline comparison for open-hole scarfed panels and panels repaired by using standard ply-by-ply replacement patch composition was achieved. Multidimensional optimization was performed to calculate the repair patch ply orientations which minimize the von Mises stresses in the adhesive. These optimal stacking sequences achieved significant reduction of the stress levels and resulted in predicted up to 75% and 85% strength restoration for flush and single ply thickness over-ply repair. These results are intended to illustrate additional design variables available for efficient composite repair design, namely the composition of the repair patch.

INTRODUCTION

The use of flush or nearly flush repairs for composite structures to maintain strict aerodynamic outer mold line requirements is a technology that is increasingly becoming essential to maintaining composite dominated aircraft structures. Unfortunately, there are only a limited number of studies on scarf repairs and patches. The published studies have described both experimental and numerical/analytical evaluation of the strains and failure loads of tension and compression loaded test articles and some of the shortcomings of current capabilities (for example [1,2]).

An analysis package that uses independent spline approximations of the displacement components *u*, *v*, and *w* for each ply of a laminate is used here to provide accurate three-dimensional solutions for stresses and displacements in composite scarf joints. The analysis maintains continuity of strains and stresses throughout a homogenous ply or adhesive while allowing strain discontinuity at ply interfaces in order to achieve interlaminar traction continuity, not achievable using conventional finite elements. Results from the analysis program have been shown to be in excellent agreement with Moiré interferometry ply level results for open hole composite laminate coupons [3,4] and for bonded doubler patches [5].

EXPERIMENTATION

A set of standard quasi-isotropic [45/0/-45/90]s specimens was used to determine virgin material tensile strength for the IM7/977-3 composite. This data was used as a standard for strength prediction analysis and as a reference for comparing strength restored by the repairs. Dog-bone specimens were used to test the repair strength. Scarfing was accomplished using a scarf-o-matic machine, shown in Figure 1. The apparatus uses a diamond bit with a pneumatic grinder that is rotated around a 2.54 cm (1.0 in) center hole and translated to provide a repeatable scarf cutout. A 1:20 scarf angle was maintained for the specimens. Additionally, the apparatus was used to cut out the scarf patches from laminates identical to those of the parent specimens.

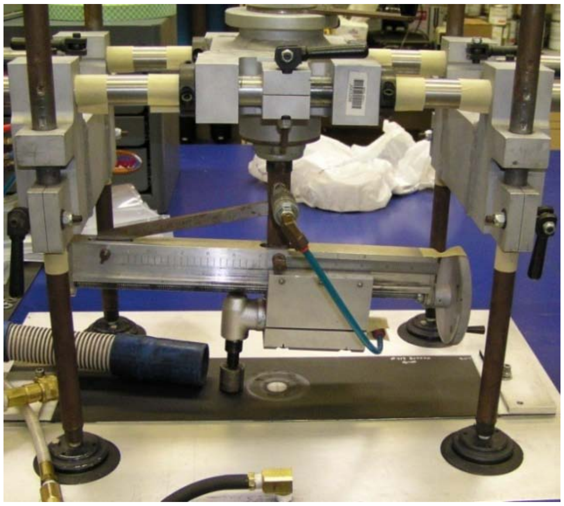

Figure 1: Scarfing apparatus

The scarf patches were bonded to the parent specimens using Cytec Fiberite's FM-300M-05 adhesive. The adhesive and overlay ply (when used) was cured using a 176ºC (350 ºF) cure cycle. The specimens were instrumented with uniaxial and rosette strain gages to monitor the far field surface strains, the strains on the patch over-ply, and strains adjacent to the patch on the parent specimen during tensile loading of the specimens. At various plan view locations on the specimen, back-to-back (front and back of the specimen) gages were mounted to measure localized bending strains caused by eccentricity of the specimen response. Glass reinforced epoxy tabs were bonded to the specimens with EPON 828 epoxy, a room temperature cure bonding system with EPI-CURE 3140 as the hardener. The tensile load was introduced into the specimens in the tab region through bolted fixtures, see Figure 2.

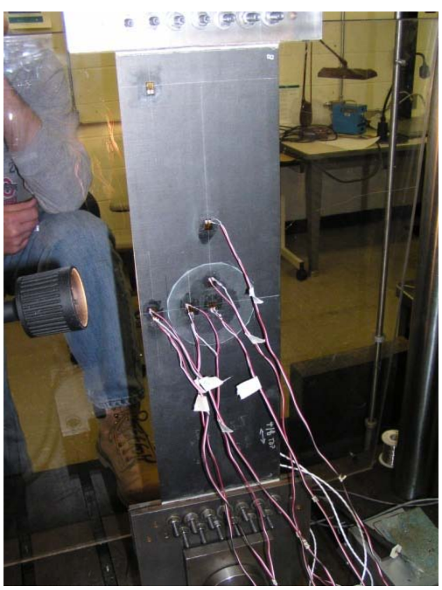

Figure 2: Specimen in load frame

Prior to testing, the loading fixtures were bolted to the two ends of the specimens. The torque on the 13 bolts on each tab was maximized to provide maximum load transfer from the fixtures to the specimen through shear transfer. This was done to prevent net section failure along the fixture bolt line. Four scarfed/not repaired and four scarfed/patched panels (with and without overply) were tensile loaded to failure. Each specimen was placed in the load frame and the strain gage leads were soldered onto the gages. The specimens were loaded in displacement control at a tension rate of 1.27 mm (0.05 in.) per minute.

ANALYSIS

The Critical Failure Volume technique introduced in [6] was used to predict the strength of the virgin, scarfed, and repaired panels. Predictions were based on the stress state in the 0° ply. Input parameters required for fiber direction strength prediction based on statistical approach include macroscopic Weibull distribution parameters for unidirectional strength in fiber direction and microscopic parameter of minimum scalable strength equal to 6δ, where δ is Rosen's ineffective length. In the case of IM7/977-3, this parameter is 6δ =0.266mm. The unidirectional composite strength properties were X_t=2.24GPa with Weibull modulus α=40 and control volume V_0=15.1cm^3.

In our analyses, it has been seen that the adhesive plays a critical role in the strength of the repaired panels. Once the adhesive fails, the stress pattern in the parent panel reverts to that of the open hole. Typically, the adhesive remains intact beyond the strength of the open hole laminate. Thus, failure of the adhesive typically results in immediate catastrophic failure of the repaired panel (see Figure 3). To delay failure in the adhesive (and thus failure of the repair), the fiber orientation in each layer of the patch and the overply was allowed to change subject to the constraint that it decreases the stress in the adhesive. The adhesive film was modeled explicitly with a thickness of 0.127mm. The modulus of the adhesive was softened for both deviatoric (von Mises) and dilatational (volumetric) strains. The instantaneous modulus was taken to be the minimum of the moduli predicted from the deviatoric and dilatational strain softening laws, which were calculated from manufacturer experimental KGR data.

Figure 3: Front and back of failed specimens

RESULTS

Simplex optimization algorithm was applied to predict the fiber orientations of the repair patch for the given quasi-isotropic adherend to maximize tensile strength retention of the repair. The optimal stacking sequence of the repair patch avoids 0° plies in the directions of the load. Such a stacking sequence prolongs the life of the adhesive and results in a predicted 13% strength increase as compared to the traditional ply-by-ply replacement. The virgin, scarfed, and repaired panels were tested to ultimate failure. Predicted strength results are compared to physical experimental results in Figure 4. It is important to note that the "Standard Repair" specimens contain a total of 9 repair layers (number of layers in the laminate plus one), while the "Optimized Repair" specimens only contain 8 repair layers. The optimized repair is 8% stronger, while being 20% lighter and 13% smaller in diameter, see Table 1.

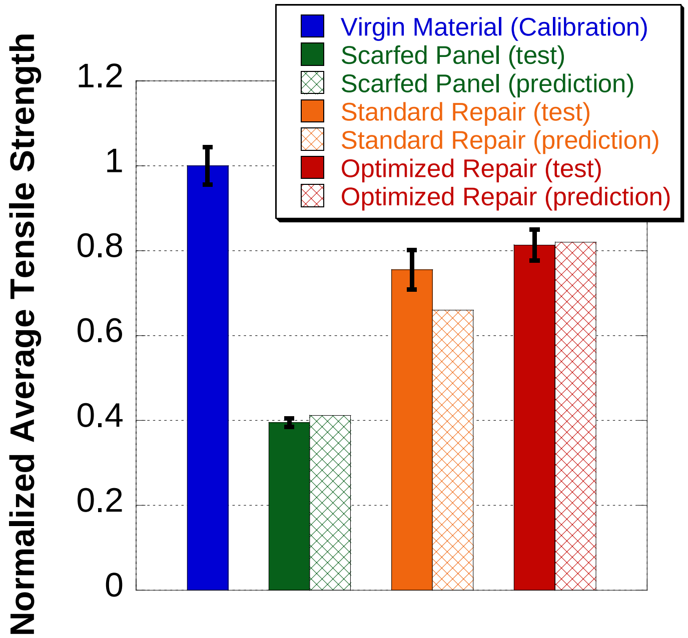

Figure 4: Tensile strength of IM7/977-3 composites

Table 1: Normalized advantages of the optimized repair in tension

	Strength	**Weight**	**Size (Diam.)**
Standard Repair	1.00	1.00	1.00
Optimized Repair	1.08	0.80	0.87

CONCLUSIONS

Mechanics of the composite repair under tensile loading with and without overlay plies were examined for nontraditional patch ply orientations. Three-dimensional nonlinear analysis was performed for repair failure prediction, which occurred as a result of the failure in adhesive. Only cohesive failure inside the adhesive was taken into account with tensile strength properties measured on bulk adhesive and KGR-1 shear response. The failure of the adherend was predicted by a statistical criterion applied to tensile fiber failure mode only. Multidimensional optimization was performed to calculate the repair patch ply orientations which reduce the von Mises stresses in the adhesive. These optimal stacking sequences achieved significant reduction of the stress levels and resulted in predicted up to 82% strength restoration for flush and single ply thickness overply repair. These results are intended to illustrate additional design variables available for efficient composite repair design, namely the composition of the repair patch.

ACKNOWLEDGMENTS

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