Evaluation of a UAV Composite Wing Spar Repair Using an Embedded Optical Fiber Rayleigh Back-Scattering Distributed Strain Sensing

Arik Bergman, Uri Ben-Simon, A. Schwartzberg, N.Y. Shemesh, Benny Glam, J. Burvin, Iddo Kressel, T. Yehoshua, Moshe Tur

EVALUATION OF A UAV COMPOSITE WING SPAR REPAIR USING AN EMBEDDED OPTICAL FIBER RAYLEIGH BACK-SCATTERING DISTRIBUTED STRAIN SENSING

A. Bergman[1], U. Ben-Simon[2], A. Schwartzberg[2], N.Y. Shemesh[3], B. Glam[3], J. Burvin[2] I. Kressel[2], T. Yehoshua[1], M. Tur[1]

[1]*School of Electrical Engineering, Tel-Aviv University, Tel-Aviv Israel*
[2]*IAI Engineering Division, Ben Gurion International Airport Israel*
[3]*IAF Aircraft Structure Branch, Tel-Aviv Israel*

ikressel@iai.co.il

ABSTRACT

A representing damaged UAV wing spar cap was repaired using bonded unidirectional composite materials. For such a repair concept, its strength and long-term durability depend on optimizing the geometry of the repair in order to minimize stress concentration in the adhesive. In order to assess the stress distribution along the repair bond-line, an optical fiber was embedded during the repair application for distributed Rayleigh back-scattering strain measurement. The fiber was placed inside the structure, therefore enabling taking strain measurements, at a high spatial resolution, under the wing skin directly on the spar repair. This type of sensing concept can also be used to monitor this critical repair over time. It also coincides with the recently introduced airworthiness requirements for UAVs, where the substantiation of structural bonded joint can be based on: "repeatable and reliable non-destructive inspection".

KEYWORDS: *Bonded composite repair, Rayleigh back-scattering strain measurement, Optical strain sensing.*

INTRODUCTION

The increasing use of high modulus composite materials for UAVs main structure imposes a challenge when repair of such component is needed, since both stiffness and strength must be restored. Two basic repair concepts can be considered for such structures: a bolted repair, where a patch is attached by fasteners over the damaged area or a more advanced concept, where the patch is bonded to the part [1]. For UAV structures, where high or medium modulus composite material is used at high percentage in the layup, the fastened concept, in most cases, cannot restore the original structure strength and stiffness. Bonded repairs are known for their ability to restore both strength and stiffness [1,2] but their design and application are challenging, especially where high stiffness has to be addressed. Major challenges in applying bonded repair are its sensitivity to adhesive thickness and surface preparation for bonding. It should also be noted that no commercially available non-destructive inspection is capable of evaluating the strength of such a patch.

In this work a representative damaged UAV wing spar cap was repaired using bonded unidirectional composite materials. Two types of bonded repair concepts were evaluated in order to select the best option for application, in terms of both design and quality of application. In order to assess the repair performance, an optical fiber was embedded during the repair application to be later used for distributed Rayleigh back-scattering strain measurement with high spatial resolution [3,4,5].

Three specimens were tested statically and under fatigue spectrum, all were monitored using the embedded optical fiber. The first two specimens, tested up to failure, were used to optimize the repair concept and the third one was a full scale wing spar portion, representing the actual repaired front spar and leading edge. This last specimen was tested up to ultimate load, followed by cyclic loading spectra, representing the full lifetimes of the structure. During this entire test, strain measurements were taken periodically with a spatial resolution of 1cm. The resulting strain distributions and their dependence on the applied load were found to predict the quality of the bonded repair. Thus, it appears that this sensing concept enables direct monitoring of bonded repair durability during both application and service.

THE BONDED REPAIR CONCEPT

The basic analytical model for stress distribution in bonded repairs was presented by Hart-Smith in the 1970s [6]. Typical bonded patch repair is shown in Figure 1. For this configuration where *t* is the thickness of both the patch and the substrate, *E* is the elastic modulus, ν is the Poisson's ratio and G_a is the adhesive shear modulus. For the configuration of Figure 1 this model predicts that the maximum shear stress occurs at the patch ends.

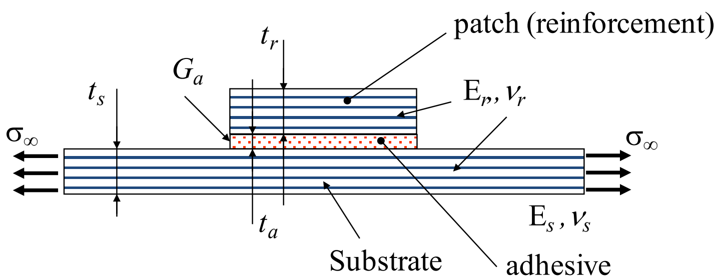


Figure 1: Bonded patch basic concept

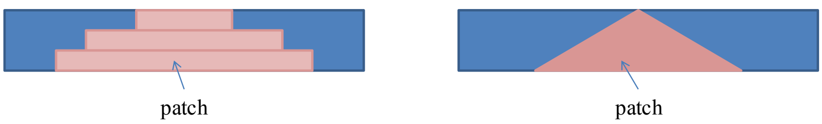
For a simplified arrangement where the thickness and material properties are the same, for both the patch and substrate, the maximum shear stress is equal to:

$$\tau_{a_{\max}} = \frac{1}{2}\beta\sigma_\infty t_s \,, \tag{1}$$

where β is defined by: Israel Aerospace Industries

$$\beta^2 = \frac{G_a}{t_a}\left[\frac{1-\nu_s^2}{E_s t_s} + \frac{1-\nu_r^2}{E_r t_r}\right] \tag{2}$$

By evaluating equations (1) and (2) it is clearly seen that the stress concentration in the adhesive is proportional to the remote stress and is not a function of the bond line length. Since we consider here unidirectional, intermediate modulus, high strength, carbon fiber composite, this issue of adhesive stress concentration is of great importance and should be minimized by proper design.
The common way to reduce the stress associated with the ends of the bonded patch repair is by introducing a scarf or stepped patch as described in Figure 2. In the two concepts the patch is bonded to the substrate with 9394 paste adhesive at room temperature under vacuum.



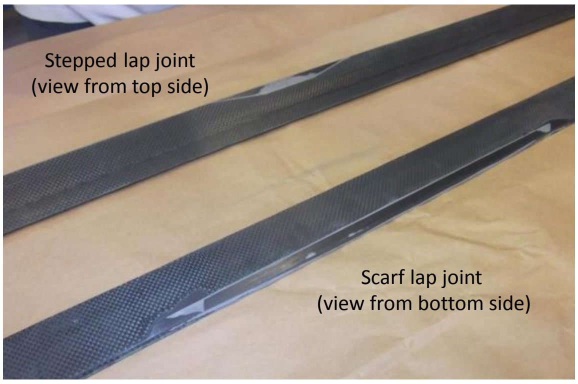
(a) (b)

Figure 2: Bonded patch basic concepts: (a) Stepped lap joints. (b) Scarf lap joint

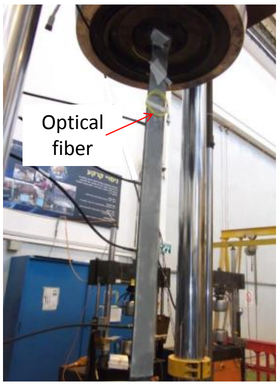
EXPERIMENTAL WORK

In order to assess the stress distribution along the repair bond-line, an optical fiber was embedded during the repair application for distributed Rayleigh back-scattering strain measurement with high spatial resolution. This type of distributed sensing is an excellent alternative to the conventional

electrical strain gauges that are discrete and can only be placed on the outer surface where adhesive stress concentrations are masked by the skin and can be missed.
The Rayleigh 'signature' of the fiber is recorded at a reference state and then when the structure with the embedded fiber is strained, the modified new reading is correlated with the reference one to produce a measure of the strain change the fiber had experienced (at a constant temperature). This is a high resolution technique (~1cm), requiring no preparation on the part of the fiber.
Three specimens were tested statically and under fatigue spectrum, all monitored using the embedded optical fiber. The first two specimens one with a stepped lap joints and the other with a scarf lap joint (Figure 3), were tested up to failure. These two specimens were used to optimize the repair concept. The third one was a full scale portion of a UAV wing front spar and leading edge, including the repair. This last specimen was tested up to ultimate load, followed by cyclic loading spectra, representing many lifetimes of the structure. During this entire test, strain measurements were taken periodically.



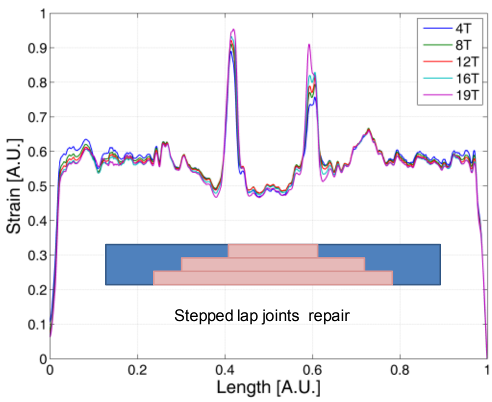
(a)



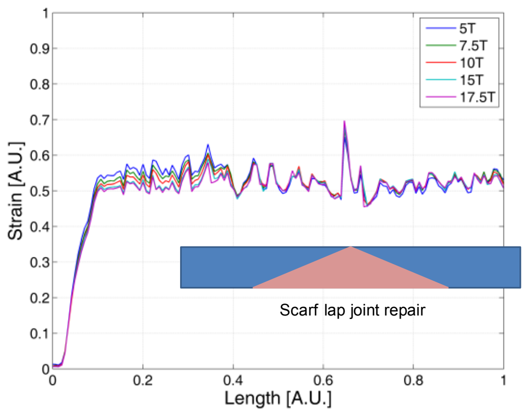
(b)

Figure 3: Bonded repairs specimens. (a) The scarf and stepped joints specimens, for orientation see fig. 2. (b) Joint specimen on the test machine.

The two repair concepts strain measurements, taken during ultimate loading tests are shown in Figure 4. It is clearly seen that the observed dependency of strain to load is highly nonlinear for stepped joint repair. This nonlinearity corresponds to sharp changes in the repair stiffness, stressing the adhesive beyond its linear limit at two locations in the repair. For the second specimen, where the repair concept was designed to avoid stress concentration, it is seen that the stress concentration at the joint critical location is very small and no nonlinearity is observed.



(*a*)

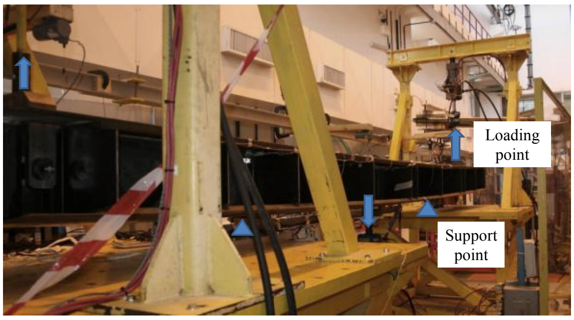


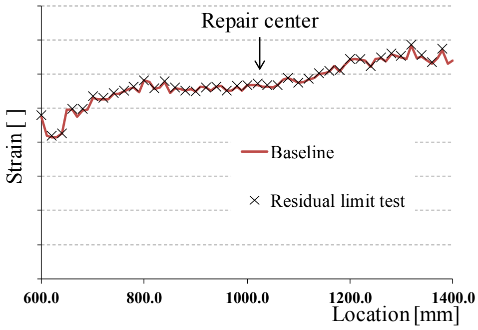
(*b*)

Figure 4: Normalized strain distribution in the repair specimens; (*a*) First specimen: stepped lap joints repair concept; (*b*) Second specimen: scarf repair with gradual stiffness change

As a result of this adhesive overstressing, the stepped lap joints specimen with sharp stiffness changes failed at approximately 66% of the ultimate failure load of the second scarf repair specimen.

Based on these results, the 3rd specimen, a 6m long UAV wing spar repaired by the scarf lap concept, was manufactured and successfully tested statically up to the ultimate design load, followed by fatigue and residual limit loading. The specimen on the test rig and strain measurements are presented in Fig. 5 *(a)* and *(b)*, respectively. Here, the repair strain distribution remained the same during the entire duration of the test, verifying that the repair airworthiness is maintained.





(*a*) (*b*)

Figure 5: UAV wing spar test article. (*a*) The specimen on the test rig. (*b*): Strain measurements at the repair area, no change was observed after static and fatigue tests.

CONCLUSION

Rayleigh back-scattering strain measurement was used for quantitative evaluation of bonded repair concepts designed for high strength and stiffness members, as required in modern UAVs. The repair concept selected withstood static loading up to ultimate, followed by fatigue and residual limit loading, without any change in strain distribution. Since this sensing approach can track such critical bonded repairs also during service, eventually also in real time, it makes it possible to monitor directly any change in stress distribution that may lead to failure. This also coincides with the recently introduced airworthiness requirements for UAVs, like the STANAG 4671 [7] where the substantiation of structural bonded joint requires: "repeatable and reliable non-destructive inspection".

REFERENCES

[1] Baker, Alan A., LR Francis Rose, and Rhys Jones. Advances in the bonded composite repair of metallic aircraft structure. Vol. 1. Elsevier, 2003.

[2] Kressel I., Ghilai G., Gali S., Hackman N., Leibovich H., Peled D., Brot A., Sol U., Grosu E., Cohen I., Ben-Noon M., Jiny S., Meir Y., Halevi R., Alon L. and Atzmoni A., “Design substantiation and application of boron-epoxy patch repair on an F-16 fuselage skin”, in: Proceedings of the 22nd ICAF Symposium, EMAS Publishing, 2003.

[3] Froggatt, Mark, and Jason Moore. "High-spatial-resolution distributed strain measurement in optical fiber with Rayleigh scatter." Applied Optics 37.10 (1998): 1735-1740.

[4] Soller, Brian, et al. "High resolution optical frequency domain reflectometry for characterization of components and assemblies." Optics Express 13.2 (2005): 666-674.

[5] Güemes, Alfredo, Antonio Fernández-López, and Brian Soller. "Optical fiber distributed sensing-physical principles and applications." Structural Health Monitoring 9.3 (2010): 233-245.

[6] Hart-Smith, Leonard John. Adhesive-bonded single-lap joints. Hampton, VA: Langley Research Center, 1973.

[7] NORTH ATLANTIC TREATY ORGANIZATION (NATO). STANAG 4671 “UAV Systems Airworthiness Requirements (USAR) for North Atlantic Treaty Organization (NATO) Military UAV Systems”, Edition 1, 2007.