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Backman, D.; Patterson, E. A.

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Fatigue Life Enhancement of Fiber Metal Laminate Materials as a Result Of Hole Cold Expansion

David Backman¹
Eann A. Patterson²

¹National Research Council
Institute for Aerospace Research
1200 Montreal Road, Building M14
Ottawa, Ontario Canada K1A 0R6

²Department of Mechanical Engineering
Michigan State University,
East Lansing, MI, USA
eann@egr.msu.edu

ABSTRACT

Fiber metal laminate materials (FML), based on a combination of aluminum and glass fibers are being promoted as potential replacements for aluminum based on their lower weight and increased fatigue life. One issue that has not been completely addressed is whether fatigue life enhancement techniques such as cold expansion are effective. Although both experimental and theoretical research has been performed looking at the effect of hole cold expansion in aluminum alloys no research has focused on measuring the fatigue life enhancement that could result from the cold expansion process in FML materials. To investigate the fatigue life enhancement associated with hole cold expansion the fatigue crack initiation period in fiber metal laminate materials both before and after cold expansion was measured. Fatigue crack growth studies were performed on FML 3-3/2 dogbone coupons and crack growth was monitored using a digital camera equipped with a high magnification zoom lens. The images were also analyzed using a digital image correlation system that allows measurement of surface strains during fatigue crack growth. The results showed that cold expansion is very effective in slowing macro-scale crack growth in fiber metal laminate materials but that it does not have a significant effect on retarding short crack formation.

INTRODUCTION

The use of fiber metal laminate materials in aerospace is increasing as large manufactures such as Airbus and smaller manufacturers such as Bombardier, investigate and integrate fiber metal laminates (FML) into aircraft structures. Fiber metal laminate materials, especially those based on a combination of aluminum and glass fibers, are being promoted as potential replacements for aluminum based on their lower weight and increased fatigue life. This has important implications from an airworthiness perspective since Federal Aviation Administration (FAA) regulations, specifically Federal Aviation Regulation (FAR) 25, requires most structural parts of an aircraft to adhere to a damage tolerant philosophy. Manufacturers typically meet this requirement in aluminum alloys by lowering the allowable design stress, whereas switching to FML type materials would allow them to increase the allowable design stress and lower the weight of the structure. The focus on manufacturing processes such as cold expansion and riveting are also more critical in FML due to the inherent tensile residual stresses that are locked into the material during the manufacturing process. Compared to monolithic aluminum alloys, crack nucleation and growth to a detectable level tends to occur more rapidly, but the overall propagation of these cracks to failure is greatly curtailed by crack bridging from the glass laminate layers[1, 2].

EXPERIMENTAL PROCEDURE

For this experiment panels of FML-3-3/2 were produced in-house by the NRC composite fabrication facility. These panels measured 12 inches by 12 inches square and were water jet cut according to the cut plan in Figure 1a and then machined to the final dimensions shown in Figure 1b. One coupon from each blank was set aside for static testing and the others were used for the fatigue test. Tension-tension fatigue testing of the FML coupons was performed at three stress levels (24, 26 and 29 ksi) with a stress ratio of 0.01. All coupons were center drilled with an open hole of 0.241 inches in diameter and half the coupons had this central hole cold expanded using split sleeve cold expansion tooling (Fatigue Technology Inc, Seattle WA). On the entry side of the coupon a 2D digital image correlation system (Correlated Solutions Inc, Columbia SC) was used to measure the strain field during cold expansion as well as to monitor strain field changes during fatigue loading. An AVT Marlin camera (Allied Vision Technologies Inc.) with a c-mount lens and an extension tube provided a high magnification image that allowed image correlation to be performed without the need for any painting or speckling of the surface. This also allowed for optical tracking and measuring of crack growth.

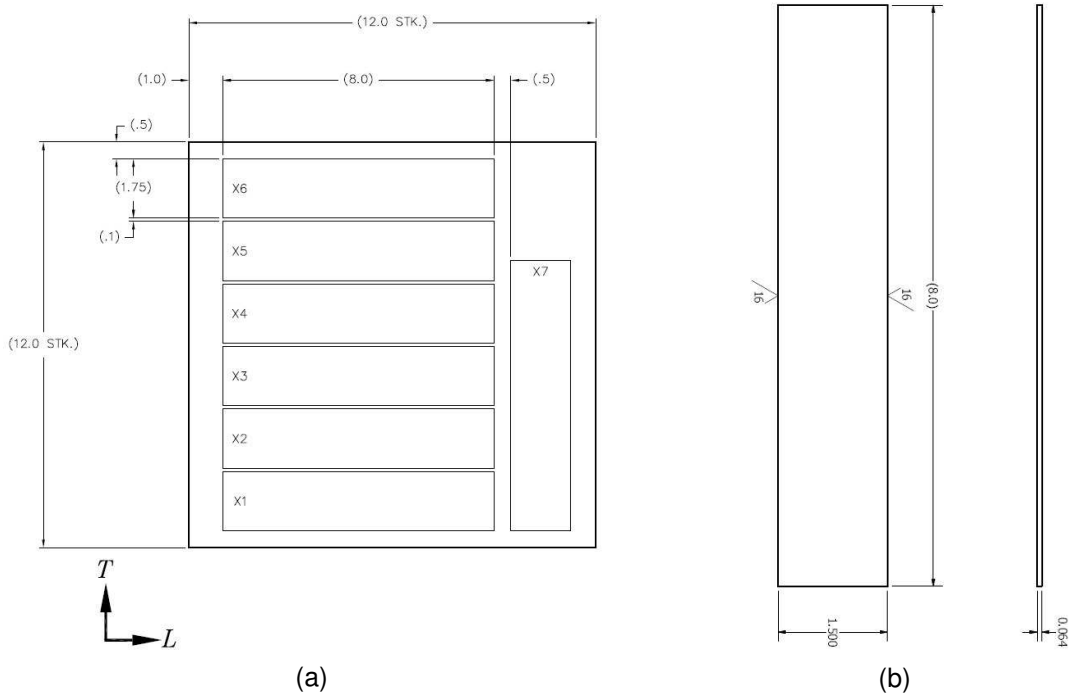


Figure 1: (a) Basic coupon dimensions and material orientations (b) coupon dimensions after machining

The cold expansion was performed with the coupons gripped in the MTS frame. This allowed reference images to be taken before cold expansion and thus surface strain could be measured during cold expansion as well as during the fatigue cycles. The test was run in force control and the failure criteria for the FML coupons was defined as the point at which the displacement on the coupons met or exceeded our threshold displacement of 0.035 inches. At this point surface cracks in the aluminum extended from the hole to the edge of the coupon on both the front and back face. By keeping the FML coupons intact, it was possible to perform ultrasound on each coupon and determine the degree of disbond between the aluminum and glass pre-preg layers.

RESULTS AND DISCUSSION

One potential issue with FML as compared to monolithic aluminum is the comparatively short time required for small cracks (0.04-0.2 inches) to form. If processes such as cold expansion are effective at lengthening the number of stress cycles required for short crack growth, it would make the acceptance of FML in standard manufacturing practice much easier. As authors such as Homan[3] and Alderliesten[1, 2] point out, residual stress in the aluminum layers is caused by the mismatch of thermal expansion coefficients that sees residual stresses locked into the aluminum layers during the high temperature curing process. It is possible that the compressive residual strains induced during the cold expansion and riveting process might offset the tensile residuals and increase the time required for short crack growth.

A modified digital image correlation (DIC) setup was placed on the exit side of the coupon, using only a single camera with a high magnification lens and no surface paint to enhance contrast. In this way, crack growth could be clearly seen and tracked from the images and surface strains could be calculated as well. The image correlation system placed on the entry side of the coupon provided excellent results. Although the idea of using inherent surface contrast of a specimen for image correlation was first demonstrated by Lopez-Crespo [4] it was used here to look at a much larger area, approximately 0.85 in². By synchronizing image capture to occur in phase with the loading it was possible to capture images only at load peaks and generate a series of images that could be used to look at the changes in the strain field as well as to optically measure crack growth. While changes in the strain field clearly showed the effect of crack growth, optical measurements of crack growth from the monochrome images provided by the AVT camera were the most reliable source of information regarding the existence of small cracks below 0.040 inches. The measurements made from these images were routinely able to track cracks lengths on the order of 0.008 inches. Figure 2 shows the crack growth curves for both open-hole and cold expanded FML coupons at the both the minimum and maximum stress levels. In both cases, cold expansion retards crack growth by a factor of approximately four compared to the open hole coupons.

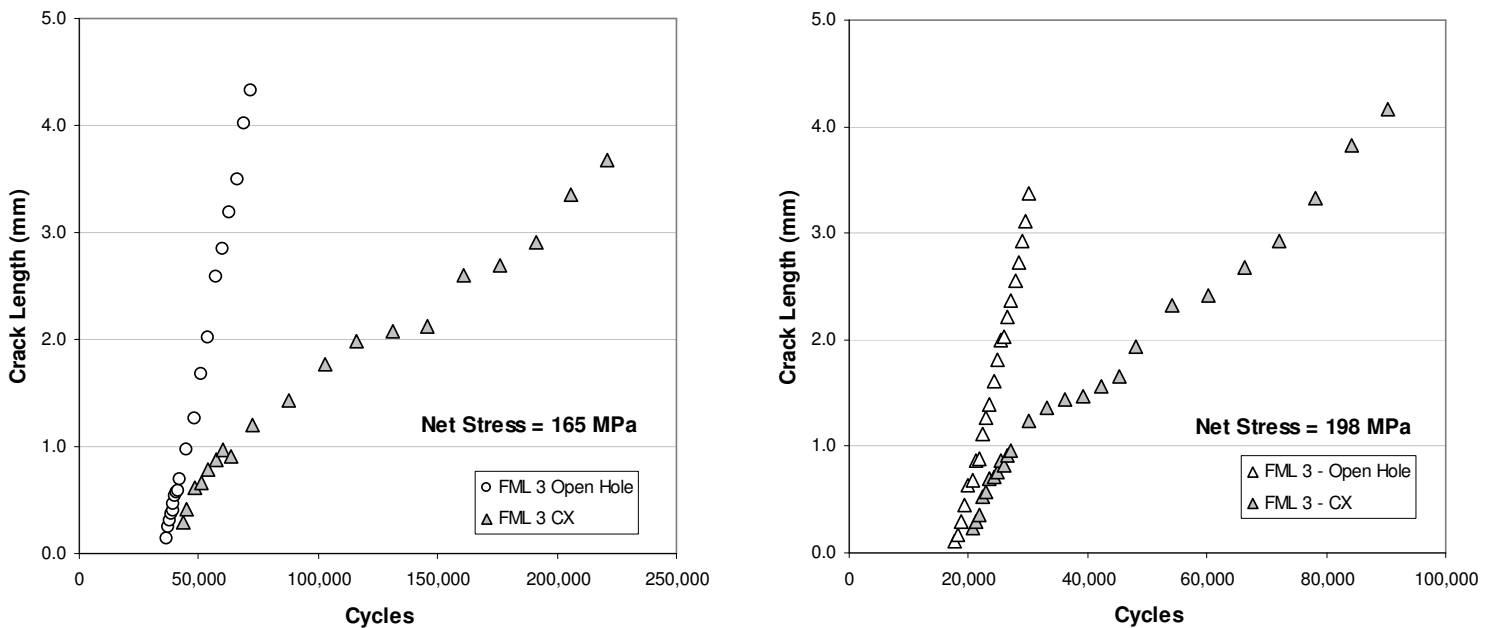


Figure 2: Crack growth curves coupons with an open hole and a cold-expanded hole (CX) at applied stress 165 MPa and 198 MPa

A plot of cycles to failure versus net stress (Figure 3) shows the overall improvement achieved with cold expansion of the hole. In monolithic materials it is the large compressive residual stresses that are responsible for retarding crack growth by providing a negative stress intensity factor in the vicinity of the open hole. Our initial hypothesis was that cold expansion in FML material would reduce the time required for short crack nucleation. Although no clear delineation exists between the short and long crack regime in FML researchers such as Homan[3] and Bradshaw[5] have defined a crack of 0.040 inches (1.0 mm) as constituting “fatigue crack initiation”. It is clear from the graphs in Figure 2 that cold expansion does little to retard “fatigue crack initiation” and only appears to have an effect on the crack once it grows past approximately 0.040 inches in length. This type of behaviour suggests that crack bridging, which does not play a role in short crack retardation, is still a key mechanism in delaying crack growth.

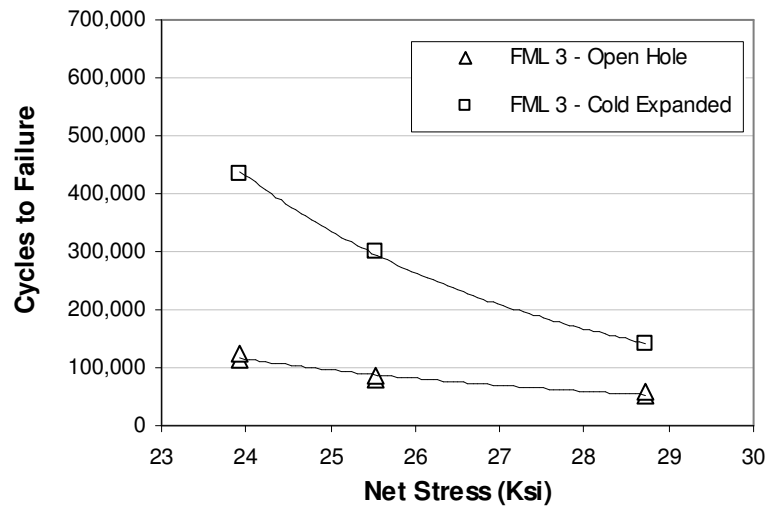


Figure 3: Cycles to failure for open hole and cold expanded FML 3 at various stress levels

After the completion of fatigue testing ultrasonic inspection in pulse echo mode was used to determine the disbond area surrounding the crack. Pulse echo mode is a more localized form of ultrasonic inspection that can discriminate between the region of disbond on the exit face and the entry face of the coupon. The ultrasonic results suggest that the area of disbond on the exit face is triangular with the apex at the tip of the crack while on the entry face the delamination is more rectangular in shape with one side of the rectangle being tangential to the tip of the crack.

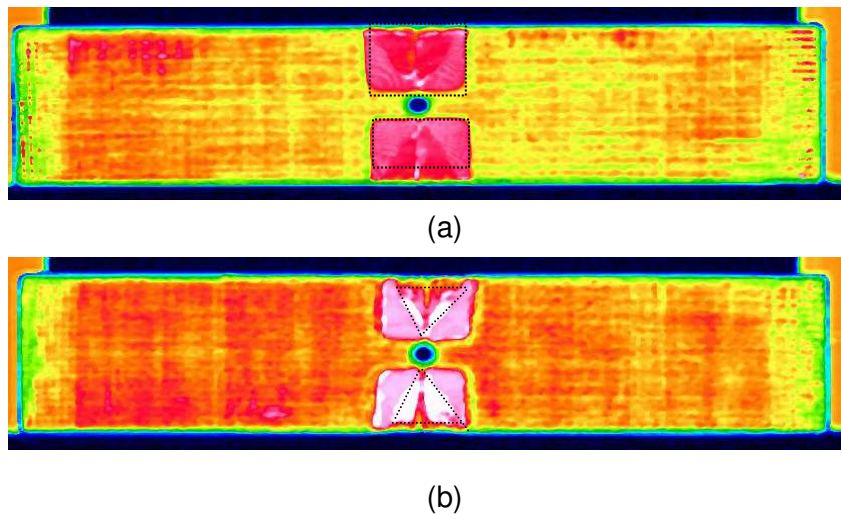


Figure 4: Post-failure ultrasonic inspection showing disbonded regions in an FML coupon (a) entry face (b) exit face of coupon with the area of the disbonds highlighted with dotted lines.

CONCLUSION

Overall, cold expansion appears to be an extremely effective way of retarding the growth of cracks in fiber metal laminate materials. However, the cold expansion process does not appear to be as effective in reducing the tendency of small cracks (>0.040 inch) to nucleate more quickly in FML. Future research will focus on better understanding this phenomenon to ascertain whether new FML variants or new cold expansion methods would be most effective at addressing this issue.

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REFERENCES

- [1] R. Alderliesten and J. Homan, Fatigue and damage tolerance issues of glare in aircraft structures. *International Journal of Fatigue* 1-8 (2006).
- [2] R. Alderliesten, M. Hagenbeek, J. Homan, P. Hooijmeijer, T. de Vries and C. Vermeeren, Fatigue and Damage Tolerance of Glare. *Applied Composite Materials* 10, 223-242 (2003).
- [3] J. Homan, Fatigue initiation in fibre metal laminates. *International Journal of Fatigue* 28, 366-374 (2006).
- [4] Lopez-Crespo, P., Shterenlikht, A., Patterson, E.A., Withers, P.J., and Yates, J.R., 2008, 'The stress intensity of mixed mode cracks determined by digital image correlation', *J. Strain Analysis*, 43(8):769-780.
- [5] R. Bradshaw and S. Gutierrez. Characterization of fatigue crack initiation and growth in hybrid al-graphite fibre composite using image analysis. *Fatigue and fracture of engineering materials and structures* 30, 766-781. 2007.