Fatigue and Residual Strength Characteristics of Fiber Metal Laminates Subjected to Incidental Damage

December 1992

R. Fredell / A. Vlot / M. Verbruggen
Fatigue and Residual Strength Characteristics of Fiber Metal Laminates Subjected to Incidental Damage

R. Fredell / A. Vlot / M. Verbruggen
Fatigue and Residual Strength Characteristics of Fiber Metal Laminates Subjected to Incidental Damage

Presented to the 1992 USAF Aircraft Structural Integrity Program Conference
1-3 December 1992
San Antonio, Texas, USA

Captain Robert Fredell, USAF
Dr. Ad Vlot
Delft University of Technology
Delft, The Netherlands

Dr. Marc Verbruggen
Structural Laminates Company
New Kensington, Pennsylvania

Abstract

Fiber metal laminates are a family of advanced hybrid aerospace structural materials consisting of thin aluminum alloy sheets adhesively bonded to alternating layers of fiber/epoxy prepregs. Two classes of laminates are available: aramid fiber reinforced ARALL® and GLARE®, which incorporates high-strength glass fibers. Fiber metal laminates have high specific tensile strength and excellent fatigue crack growth resistance, while retaining the good workshop properties of monolithic aluminum alloys. ARALL® 3, the aramid/epoxy/7475-T76 laminate, is currently in production and flight test as the skin of the C-17 aft cargo door.

The well-known sensitivity of conventional advanced composites to incidental damage such as impact has slowed the widespread application of these materials to thin, damage tolerance-critical primary structures such as fuselage pressure cabin skins. Therefore, a detailed investigation was made into the fatigue and residual strength characteristics of GLARE® and ARALL® following damage typically encountered in the service environment. Comparative impact tests were performed on monolithic aluminum, fiber metal laminates, and carbon thermoplastic composites. Fatigue and residual strength tests were carried out on impact- and scratch-damaged fiber metal laminates. The results of this assessment demonstrate the superior tolerance of GLARE® laminates to in-service damage and the extremely slow crack growth characteristics of all fiber metal laminates.

Repair criteria based on the blunt notch strength of the laminates are proposed for in-service damage to riveted fiber metal laminate structures. Scratches which penetrate less than 30% of the laminate thickness should be left unrepaird. Impacts which do not cause perforation may also be left alone. Scratches and small cracks which expose the fiber/epoxy prepreg layer(s) should be environmentally sealed. In general, techniques used for the repair of aluminum structures also apply to laminates.
Introduction

The family of highly fatigue resistant fiber metal laminates ARALL\textsuperscript{a} and GLARE\textsuperscript{a} were developed primarily at Delft University over the past decade [1-9]. The laminates consist of thin high-strength aluminum alloy sheets bonded together with strong fiber/adhesive prepregs, as shown in figure 1. The exceptional fatigue resistance of these materials is attributed to the crack bridging effect of intact fibers in the wake of a propagating fatigue crack. Crack bridging results in a load transfer away from the crack tip into the fibers and restraint on crack opening, thereby reducing the stress intensity factor at the crack tip [1], as shown in figure 2.

Fiber metal laminates are commercially available in six grades, as shown in figure 3. Important mechanical properties of the materials tested in this program are given in Table 1. Both unidirectional and 0/90 cross-plied fiber layups are available. Thus, a wide range of tailorable properties is available to the aircraft designer. This paper will discuss the following characteristics of fiber metal laminates:

- fatigue resistance,
- environmental stability,
- impact resistance,
- fatigue/residual strength properties following incidental damage, and
- proposed repair criteria for riveted fiber metal laminate fuselage structures.

<table>
<thead>
<tr>
<th>Property</th>
<th>2024-T3</th>
<th>ARALL 3, 3/2\textsuperscript{1}</th>
<th>GLARE 3, 3/2\textsuperscript{2}</th>
<th>GLARE 4, 3/2\textsuperscript{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tensile ultimate strength, MPA</td>
<td>L</td>
<td>455</td>
<td>765</td>
<td>717</td>
</tr>
<tr>
<td></td>
<td>LT</td>
<td>448</td>
<td>352</td>
<td>716</td>
</tr>
<tr>
<td>Tensile yield strength, MPA</td>
<td>L</td>
<td>359</td>
<td>565</td>
<td>305</td>
</tr>
<tr>
<td></td>
<td>LT</td>
<td>324</td>
<td>290</td>
<td>283</td>
</tr>
<tr>
<td>Elastic tensile modulus, GPa</td>
<td>L</td>
<td>72</td>
<td>68</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>LT</td>
<td>72</td>
<td>49</td>
<td>58</td>
</tr>
<tr>
<td>Ultimate failure strain, %</td>
<td>L</td>
<td>19</td>
<td>1.8</td>
<td>4.7</td>
</tr>
<tr>
<td></td>
<td>LT</td>
<td>19</td>
<td>6.4</td>
<td>4.7</td>
</tr>
<tr>
<td>Bearing ultimate strength, MPA (e/D = 2)</td>
<td>L</td>
<td>890</td>
<td>669</td>
<td>819</td>
</tr>
<tr>
<td></td>
<td>LT</td>
<td></td>
<td>655</td>
<td></td>
</tr>
<tr>
<td>Gross blunt notch strength, MPA (circular hole, W = 100 mm, D = 25 mm)</td>
<td>L</td>
<td>311</td>
<td>409</td>
<td>372</td>
</tr>
<tr>
<td></td>
<td>LT</td>
<td>311</td>
<td>264</td>
<td>372</td>
</tr>
<tr>
<td>Gross sharp notch strength, MPA (center crack specimen, W = 100 mm, 2a\textsubscript{c} = 25 mm)</td>
<td>L</td>
<td>279</td>
<td>248</td>
<td>295</td>
</tr>
<tr>
<td></td>
<td>LT</td>
<td>279</td>
<td>186</td>
<td>295</td>
</tr>
<tr>
<td>Density, g/cm\textsuperscript{3}</td>
<td></td>
<td>2.78</td>
<td>2.33</td>
<td>2.52</td>
</tr>
</tbody>
</table>

\textsuperscript{1} MIL HDBK 5, "S" basis allowables

\textsuperscript{2} Structural Lamminates Company, "typical" values
Fatigue Resistance

The fatigue resistance of fiber metal laminates is well known; figure 4 shows a typical example. It presents the crack growth behavior of 100 mm wide unstiffened sheets with central sawcuts under constant amplitude fatigue of 6-120 MPa gross stress. Not surprisingly, the sawcut in a 2024-T3 sheet progressed to failure after only a few thousand cycles, while the sawcuts in the GLARE specimens grew slowly and stably at a near-constant rate. After 500,000 cycles, both GLARE specimens remained intact.

Environmental Stability

ARALL and the other members of the fiber metal laminate family have been designed from the outset to be durable, supportable materials. Only stable, corrosion-resistant alloys and tempers have been chosen (2024-T3 and 7475-T76). Coating systems (phosphoric or chromic acid anodizing plus corrosion-inhibiting BR-127 primer) were selected to provide both good adhesion and excellent long-term corrosion resistance. The epoxy resin used, AF163-2 from 3M, is a well-characterized, durable, high-performance adhesive. Although extremely aggressive environments will eventually cause general corrosion of the outer surface of the laminate, just as it would with monolithic aluminum, deep pitting and perforation are precluded in practice because of the barrier function of the (inert) prepreg layers. A conservative practice, however, involves placing a thin, adhesively bonded barrier patch over deep gouges which penetrate the fiber layer(s), if they occur.

A large portion of the Ph.D. work of Verbruggen [10] concerned the environmental durability of ARALL laminates. He tested ARALL under diverse long-term static load conditions for periods of up to three years in various environments such as artificial salt water, distilled water and lab air, at temperatures of up to 70°C. No relaxation of residual stresses in the laminate was measured, and moisture pickup by the resin was orders of magnitude slower than with conventional aramid/epoxy composites, because of the existence of the outer aluminum layers, which force any moisture absorption to occur along the edges of the laminate. The long-term environmental durability of fiber metal laminates is expected to be comparable to or better than its constituent aluminum sheets. Conventional aluminum corrosion prevention and control practices apply.
Impact Characteristics

Most advanced composite materials suffer from poor out-of-plane mechanical properties. This renders thin composite skins extremely susceptible to impact damage from ground handling, hail, etc. The relative difficulty of locating and assessing such damage, when it occurs, compounds the problem.

Impact damage to fiber metal laminates has been characterized extensively and modeled analytically by Vlot et al. [11,12]. He found that cross-plied variants of GLARE\textsuperscript{a} are especially resistant to impact. Vlot tested thin specimens of unidirectionally reinforced ARALL\textsuperscript{a} 2, cross-plied GLARE\textsuperscript{a} 3, 2024-T3 aluminum and a quasi-isotropic carbon fiber/thermoplastic composite known for its high toughness (APC-2). Sample thicknesses were 1.4 mm for 2024 and the laminates, and 2.0 mm for APC-2, chosen to give approximately equal areal densities (mass per unit area). The specimens were approximately 125 mm square, and were clamped in a rigid steel frame. The impacts were made with a 7.5 mm radius hemispherical steel impactor. Low-velocity impact testing (up to 10 m/s) occurred in a drop-tower arrangement; the impactor mass was 575 g. High-velocity testing (up to 100 m/s) involved a gas gun which shot a 23.3 g projectile at the specimen.

Figure 5 compares the respective impact energies required to cause visible cracking. At both low and high impact velocities, the GLARE\textsuperscript{a} 3 showed higher resistance to cracking than 2024-T3, and at least an order of magnitude higher resistance than APC-2 carbon/thermoplastic. The ARALL\textsuperscript{a} results fell somewhere between 2024 and APC-2. Ultrasonic inspection showed that delaminations in the GLARE\textsuperscript{a} were limited to an area approximately the size of the visible dent (about 25 mm diameter maximum at 60 J), while delaminations in the APC-2 were much more extensive even at substantially lower energy levels, as seen in figure 6. The exceptional impact performance of GLARE\textsuperscript{a} 3 has been attributed to a favorable high strain rate strengthening phenomenon which occurs in glass fibers, combined with their relatively high failure strain. The lower impact resistance of ARALL\textsuperscript{a} laminates is also attributable to its fiber characteristics, most notably its modest strain to failure (about 2%) [12].

Fatigue and Residual Strength of Impacted Laminates

The current effort included an investigation into the fatigue and residual strength characteristics of standard 3/2 layups of cross-plied GLARE\textsuperscript{a} and unidirectional ARALL\textsuperscript{a} following damage typically encountered in the service environment. Fatigue and
residual strength tests were carried out on impact-damaged fiber metal laminate specimens 300 mm long by 160 mm wide. The specimens were subjected to low-velocity impact conditions as described in the preceding section. Impacts up to 13 J for ARALLₙ 3 (t = 1.33 mm) and 44 J for GLAREₙ 3 (t = 1.40 mm) and GLAREₙ 4 (t = 1.65 mm) produced a range of damage from dents with no cracking to perforation. Specimens were subjected to constant amplitude fatigue at stress amplitudes and cycles considered to be typical for potential fuselage applications prior to residual strength testing.

A clear view of the residual stresses present in a dent is the key to understanding the fatigue behavior or impacted laminates. At the moment of impact, some of the impact energy is stored in the sheet, in the form of both plastic and elastic deformations. After impact, the sheet springs back, putting tension on the concave (impacted) side of the dent, while the convex side of the dent is placed in compression. When the impacted specimen is placed in overall tension (as in the present fatigue tests), a complex combination of springback, bending, and (ex)tension results. This allows the convex surface to remain in compression up to very high gross stress levels, while the resulting tensile strain in the heavily plastically deformed region at the edge of the dent on the impacted side has a magnitude of 1.5 to 2 times the nominal strains outside the dent [11].

ARALLₙ 3 specimens were impacted, then subjected to 20,000 cycles at 5-105 MPa before residual strength testing. These levels were based on estimated C-17 cargo door stress levels for 2-1/2 lifetimes. Impacts in 3/2 ARALLₙ 3 layups caused cracks in the back aluminum layer at energies from 5 J upwards. The 13 J impact caused perforation (through-cracking) of the specimen. Cracks due to impact in ARALLₙ 3 occurred perpendicular to the fiber direction, except for the perforating impact (13 J), which resulted in a Y-shaped branched crack. In no case did the cracks caused by impact grow during fatigue cycling.

The results of gross residual strength testing after impact and fatigue are shown in figure 7. The gross blunt notch strength of ARALLₙ 3 is plotted as a reference. (As most fiber metal laminate fuselage structures are anticipated to be riveted assemblies, and as the vast majority of repairs performed today are riveted repairs, the blunt notch strength provides a good benchmark to classify damage as either incidental or needing repair.) The results show that while ARALLₙ is sensitive to impact damage, perforation (through-cracking) occurs before the blunt notch strength is compromised. Impact damage did not grow in 20,000 fatigue cycles.
The GLARE\textsuperscript{a} 3 specimens were impacted, then subjected to constant amplitude fatigue cycles at 6-120 MPa prior to residual strength testing. This much more demanding profile than for the ARALL\textsuperscript{a} 3 specimens represents three lifetimes of service for a narrow-body aircraft such as the Boeing 737, at stress levels considered typical for hypothetical a GLARE\textsuperscript{a} 3 fuselage. 3/2 GLARE\textsuperscript{a} 3 layups resisted cracking in the back aluminum layer to impacts of almost 30 J.

In contrast to ARALL\textsuperscript{a} 3, cracks in GLARE\textsuperscript{a} 3 due to impact always occurred parallel to the metal rolling (L) direction. Through-penetration occurred at 38 J. In the specimens loaded in the L direction, crack growth during fatigue cycling occurred only on the front (impacted) side of the 38 and 44 J samples, after 160,000 and 90,000 cycles, respectively. Figure 8 shows the crack which grew from the radius of the 38 J impact. Cracks initiated and grew slowly from the heavily plastically deformed radius of the dents, but were confined to only the surface aluminum layer. This is consistent with [11], where cracks in dented 2/1 ARALL\textsuperscript{a} 2 laminates grew only in the impacted layer.

Impact specimens stressed in the long-transverse (LT) direction had the added disadvantage of the impact crack running perpendicular to the load direction. Only the 37 J specimen showed any fatigue crack growth, which again was confined to the front metal layer.

None of the GLARE\textsuperscript{a} 3 specimens which suffered a penetrating impact failed in 270,000 fatigue cycles. A contrast with impacted monolithic aluminum subjected to fatigue can be seen in figure 9. Three specimens (2024-T3, GLARE\textsuperscript{a} 3 L, and GLARE\textsuperscript{a} 3 LT) were subjected to penetrating impacts in the energy range from 37 to 46 Joules. All underwent subsequent constant amplitude fatigue testing at stress amplitudes considered typical for the materials: 5-105 MPa for 2024, and 6-120 MPa for GLARE\textsuperscript{a} 3. The GLARE\textsuperscript{a} specimens exhibited slow, stable crack growth in their surface (impacted) aluminum layers. The damage in the 2024 specimen did not grow for almost 180,000 cycles, at which time it grew to catastrophic failure after only a few thousand additional cycles. The GLARE\textsuperscript{a} 3 specimens remained intact for 270,000 cycles and were subsequently pulled to static failure.

The results of the residual strength tests done after impact and fatigue are shown in figure 10. Again, the gross blunt notch strength is plotted as a reference. GLARE\textsuperscript{a} 3 shows significantly greater cracking resistance than ARALL\textsuperscript{a} (cf. figure 7). While the more demanding GLARE\textsuperscript{a} 3 fatigue profile did cause some damage growth in 270,000 cycles, the extremely slow crack growth characteristics for which laminates are known
were retained, and crack growth was limited to the more easily inspectable impacted side.

**Fatigue and Residual Strength of Scratched Laminates**

Another type of typical incidental damage seen in the field is the surface scratch. In the case of fiber metal laminates, this problem is of particular interest, especially if the scratch should happen to penetrate the fiber layer(s) on which the material system depends for its exceptional fatigue resistance.

Simulated scratches were placed perpendicular to the longitudinal (L) or "main" fiber direction in samples of 3/2 ARALL\(^n\) 3 and 3/2 GLARE\(^n\) 3. For the 3/2 GLARE\(^n\) 4 material, (two-thirds of the fibers in the L direction, one-third in the long-transverse (LT) direction), scratches were placed perpendicular to the LT direction. The scratches were made with a rotating "slitting saw," which resulted in a narrow, flat-bottomed cut. Some minor delamination could be observed with the naked eye following the cutting process. "Scratch" depths ranged from 0.15 mm to 0.70 mm, corresponding to 12 to 54% of the sample thickness. The "scratch" covered the center 40 mm of the 160 mm wide specimen. An example has been sketched in figure 11.

Eddy current inspection techniques have been developed which reliably measure the depth of such scratches in fiber metal laminates; they are reported in [13].

**ARALL\(^n\) 3.** Seven "scratched" specimens were subjected to 20,000 cycles of constant amplitude fatigue from 5 to 105 MPa at 10 Hz in lab air. The only specimen which showed any fatigue crack growth was the 0.70 mm deep "scratch" specimen. Its initial 40 mm long damage grew by 5 mm in the surface aluminum layer only.

The eighth specimen, with a 0.40 mm deep "scratch," was fatigued at a substantially higher stress level (6-120 MPa) and at a lower frequency (1Hz) for three times as many cycles (60,000). Fatigue testing was done at room temperature with the specimen immersed in distilled water, to better simulate the effects of a moist environment. No fatigue crack growth occurred. After fatigue testing, the specimen remained immersed in distilled water without load for 43 days (1,032 hours), after which it was immediately pulled to static failure. Failure occurred at a gross stress of 621 MPa, compared with 628 MPa for the 0.40 mm scratch specimen fatigued at 5-105 MPa, 10 Hz in lab air.
The results of the static residual strength tests performed on the "scratched" ARALL© 3 specimens after fatigue are shown in figure 12. One can see the progressive weakening of the laminate as the damage depth increases. Failures occurred across the reduced net section of the scratch.

**GLARE© 3.** Five "scratched" specimens were subjected to 270,000 cycles of constant amplitude fatigue from 6 to 120 MPa at 10 Hz in lab air. This increased level of fatigue loading resulted in measurable fatigue damage in the three most deeply scratched specimens.

The 0.55 mm deep "scratch" specimen which showed fatigue crack growth of approximately 12 mm in the surface aluminum layer. Crack growth occurred after 200,000 cycles. Fatigue damage in the two deepest scratches was more significant.

The 0.64 mm deep specimen showed cracking after 100,000 cycles. Cracks grew to a 29 mm total extension of the sawcut in 270,000 cycles. Through-the-thickness cracking occurred, although the crack in the scratched layer was always longer than the crack on the back side. C-scans of the specimen after fatigue testing showed the kind of "controlled delamination" along the crack flanks that has been noted by various other writers describing fatigue of fiber metal laminates.

Crack growth in the 0.79 mm deep specimen showed behavior quite similar to the 0.64 mm specimen. Crack extension of the scratch was 32 mm, resulting in an effective front side crack length of 72 mm. Back side cracking was 60 mm long. This similarity with the 0.64 mm scratch specimen can be explained by looking at the laminate cross-section, which reveals that the deepest (0.79 mm) scratch merely penetrated deeper into the second aluminum layer without further cutting any more fibers in the (load-bearing) L direction.

Figure 13 shows the residual strength behavior of the scratched GLARE© 3 specimens after fatigue. The stair-step appearance corresponds closely to the laminate structure, as discussed previously. As would be expected, the largest reduction in static strength occurred when a load-bearing fiber layer was severed.

Some interesting phenomena were observed in the scratched specimens. Stable tearing of the "crack front" (or sawcut) at an angle of approximately 50° from the sawcut line occurred during the static ultimate test in the 0.25 and 0.40 mm scratch specimens. In all specimens, as the loads increased towards failure, massive
delaminations occurred in an elliptical shape around the sawcut, resulting in a bulging-out of the outer aluminum layer. After both these events were observed, but just prior to the (expected) complete tensile failure of the scratched section, grip failure occurred in the 0.40 mm scratch specimen. In figure 14, the stable tearing and bulging of the outer (cut) aluminum layer can be seen in an elliptical shape around the fatigue-extended sawcut. In figure 15, the outer aluminum layer has been etched away, revealing a large elliptical delamination area. The presence of intact fibers at the crack tip demonstrates the stable, damage tolerant behavior of the laminate up to failure. The tearing or branching of the advancing crack tip, accompanied by vast areas of delamination, manifests the "smart material behavior" of laminates, in which the stress concentration of the advancing crack is relieved by spreading the failure over a much larger area [14].

GLARE® 4. In this group, the specimens were scratched perpendicular to and loaded in the LT direction. Four "scratched" specimens underwent 270,000 cycles of constant amplitude fatigue from 5 to 100 MPa at 10 Hz in lab air. The only specimen which showed any fatigue crack growth was the 0.70 mm deep "scratch" specimen. Its initial damage grew by 5 mm in the surface aluminum layer only.

Figure 16 shows the residual strength behavior of the scratched laminates following fatigue. The sharp drop in residual strength at a scratch depth of 30% of the laminate thickness corresponds with cutting of the load-bearing fiber layer.

Discussion Figure 17 recapitulates the data gathered in this section in a slightly different form. Residual strength data are normalized by dividing by the gross blunt notch strength of the respective materials. Scratch depths are presented as a percentage of the total respective sheet thickness. What is clear from the surprisingly tight band that results (given the wide range of fatigue pre-exposure) is that fiber metal laminates retain better than blunt notch strength in the presence of scratches as deep as 30% of their total thickness.

A Repair Criterion for Fiber Metal Laminates

The preceding tests show that incidental damage does not compromise the excellent fatigue crack growth resistance of fiber metal laminates. Incidental damage in laminates can be treated as a static problem, instead of the durability concern that exists for damaged thin-skinned monolithic aluminum structures.
Vlot [11] stated that impacts which cause no cracking do not affect the gross static strength of ARALL fiber metal laminates. He said further that back side cracks will reduce the residual static strength of ARALL with impact damage (yet without fatigue) to the laminate strength with an open hole of the same dimension. The strength drops below the blunt notch strength when the impact energy is great enough to cause a through crack, eventually approaching the saw cut strength as a lower asymptote. This is generally consistent with the present tests, where fatigue loading was experienced in addition to impact damage, except that even a non-cracking impact caused some loss of static strength. Back side cracks reduce the static strength further, while remaining above the gross blunt notch level, and penetrating cracks reduce the residual strength after fatigue to below the gross blunt notch figure.

To apply these results and develop a repair criterion for impact damaged laminates, recall that for riveted structures, the blunt notch strength also provides a good benchmark to classify damage as either incidental or needing repair. In fact, most riveted repairs cannot restore an overall panel strength higher than blunt notch unless extreme care is taken in their detail design and installation. Thus, incidental damage to riveted fiber metal laminate structures which does not reduce the overall strength of a panel below the blunt notch strength need not be repaired. A recommended exception to this is the environmental sealing of deep scratches which completely penetrate the outer aluminum layer, exposing the fiber layer. In this case, a thin bonded aluminum patch acts to renew the environmental barrier function of the damaged outer layer.

Impacts to laminates which do not cause cracks should be left unrepaired. If cracking occurs and is limited to the back (unimpacted) side only, it should be sealed from the environment. Only in the case of penetrating cracks, which are visible in the surface (impacted) aluminum layer, should the laminate be repaired. For scratches, a rough "rule of thumb" of 30% of the laminate thickness is proposed as the threshold for repair. Scratches which penetrate the outer aluminum layer (generally 0.3 mm), yet are less deep than 30% of the total laminate thickness, should be sealed. Similar tests on larger panels are planned.

Most repair practices for monolithic aluminum structures (e.g., drilling, riveting, adhesive bonding) also apply to fiber metal laminates [13]. However, one typical aluminum maintenance practice which should be avoided in laminates is "stop drilling." Stop drilling effectively extends the life of a cracked monolithic structure by temporarily reducing the stress concentration of a crack tip. However, with laminates, intact fibers in the wake of a crack tip already perform that function by limiting crack opening
displacement. Stop-drilling a crack in a laminate effectively eliminates the crack opening restraint by removing those fibers. Figure 18 shows how the growth of a stop-drilled crack in GLARE\textsuperscript{a} 3 (dashed line) actually accelerates after stop-drilling.

**Summary**

A detailed investigation was made into the fatigue and residual strength characteristics of the fiber metal laminates GLARE\textsuperscript{a} and ARALL\textsuperscript{a} following damage typically encountered in the service environment. Comparative impact tests showed a general trend of increasing impact resistance from carbon thermoplastic composites (poorest) to ARALL\textsuperscript{a}, monolithic aluminum 2024-T3, and GLARE\textsuperscript{a} 3 (best).

Fatigue and residual strength tests carried out on impact- and scratch-damaged fiber metal laminates demonstrated the excellent tolerance of laminates to in-service damage. The extremely slow crack growth characteristics of laminates were not deteriorated by scratches. Impacts which caused perforations (through-cracking) in GLARE\textsuperscript{a} and ARALL\textsuperscript{a} continued to exhibit the extremely slow fatigue crack growth for which the laminates are known.

Repair criteria based on the blunt notch strength of the laminates have been proposed for in-service damage to riveted fiber metal laminate structures. Scratches which penetrate less than 30\% of the thickness should be left unrepaired; however, scratches which expose the fiber/epoxy prepreg layer(s) should be environmentally sealed. Impacts which cause no cracks on the front (impacted surface) may also be left alone, except that the small cracks which may occur in the back (unimpacted) aluminum layer should be sealed. In general, techniques used for the repair of aluminum structures also apply to laminates.
References


Figure 1. Typical fiber metal laminates 3/2 layup.

Figure 2. Schematic showing crack bridging by intact fibers in crack wake [1].
GLARE 1: 7475-T76 aluminum; unidirectional glass prepreg; 0.5% post-stretched
GLARE 2: 2024-T3 aluminum; unidirectional glass prepreg; non-stretched
GLARE 3: 2024-T3 aluminum; 50/50 cross-ply glass prepreg; non-stretched
GLARE 4: 2024-T3 aluminum; 67/33 cross-ply glass prepreg; non-stretched

ARALL 2: 2024-T3 aluminum; unidirectional aramid prepreg; non-stretched
ARALL 3: 7475-T76 aluminum; unidirectional aramid prepreg; 0.5% post-stretched

Figure 3. Currently available product forms of fiber metal laminates.

Figure 4. Fatigue crack growth behavior from a sawcut of various aerospace sheet materials.
Figure 5. Cracking resistance of various aerospace sheet materials subjected to impact.

Figure 6. Delamination performance of impacted GLARE® 3 and quasi-isotropic APC-2 carbon/thermoplastic composite. (Equal areal densities)
Figure 7. Residual strength of 3/2 ARALL® 3 laminates after impact and fatigue.

Figure 8. Photograph of a fatigue crack in a 3/2 GLARE® 3 laminate after 38 J impact and 166,000 cycles of 6-120 MPa fatigue.
Figure 9. Contrasting fatigue behavior of monolithic aluminum and GLARE® 3 laminates following perforating impacts.

Figure 10. Residual strength of 3/2 GLARE® 3 laminates after impact and fatigue.
Figure 11. "Scratched specimen" used for fatigue and residual static strength testing.

Figure 12. Residual strength of "scratched" ARALL\textsuperscript{3} specimens after fatigue cycling.
Figure 13. Residual strength of “scratched” GLARE 3 (L) specimens after fatigue cycling.

Figure 14. Photograph of “scratched” 3/2 GLARE® 3 (L) specimen which failed in grips. Skin bulging and stable tearing can be observed.
Figure 15. Photograph of “scratched” 3/2 GLARE® 3 (L) specimen after etching of the outer aluminum layer. The delaminated areas of the prepreg (lighter areas) can be observed.

Figure 16. Residual strength of “scratched” GLARE® 4 (LT) specimens after fatigue cycling.
Figure 17. Normalized residual strength of "scratched" fiber metal laminate specimens after fatigue cycling.

Figure 18. The effect of "stop-drilling" a fatigue crack in a fiber metal laminate specimen.