METAL PLASTICITY AND SPECIMEN SIZE EFFECTS IN EVALUATION OF ARALL® LAMINATES NOTCHED PANEL RESIDUAL STRENGTH.

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ARALL® Laminates are a family of materials made of alternating layers of thin aluminum sheets bonded by adhesive impregnated with high strength aramid fibers. The principal benefit of the resulting fibrous composite is ability to impede and self arrest crack growth. In view of the potential ARALL Laminates applications, such as tension dominated fatigue and fracture critical structures, an accurate assessment of notched ARALL Laminates residual strength response is required. In this paper, test results on the residual strength of notched ARALL Laminate panels are presented. In addition, finite element analysis results, which show the effect of metal plasticity and specimen size on the residual strength, are described. Practical significance and implication of these results on notch design allowables, damage tolerance, and small scale scale coupon to large panel test data transition are discussed.

INTRODUCTION

ARALL® Laminates are a family of materials made of thin aluminum sheets alternating with plies of epoxy prepreg containing unidirectional aramid fibers. Uniting high strength aluminum and strong aramid fibers in a bonded arrangement imparts high specific strength and excellent fatigue resistance of advanced composites, while retaining the traditional durability and fabricability advantages of metals. More complete description of ARALL Laminates and their properties can be found in [1]. One of the variants of ARALL Laminates, 3/2 ARALL-2, is shown in Figure 1. The 3/2 designation denotes a laminate arrangement consisting of 3 aluminum and 2 aramid/epoxy prepreg plys.

The outstanding fatigue crack growth resistance of ARALL Laminates is mainly due to retardation and self-arrest of fatigue cracking by transfer of loads from the fatigue cracked metal to the unbroken aramid fibers bridging the metal cracks. When loaded in the fiber direction, ARALL panels containing fatigue cracks show residual strength significantly higher than monolithic aluminum [1]. If, instead, cutouts (slots and holes) or penetrations (i.e. from engine rotor failure) are introduced, then there are no bridging fibers and the laminate residual strength is not greatly improved over that of aluminum. In view of potential ARALL Laminates damage tolerant applications, such as fuselage and lower wing skins, the understanding of the failure mechanisms and ability to predict ARALL residual strength behavior in the absence of fiber bridging are required.

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Presently, there are methods for predicting residual strength of metal specimens, such as one proposed by Feddersen [2]. Alternatively, several composite material approaches, applicable to residual strength prediction of notched composites, are described in [3]. Since ARALL Laminates are a combination of metal and composite, it is important to identify which criteria (metal vs. composite) are governing for a particular application.

In this paper notched panel residual strength data and accompanying finite element analysis results are described. The results show the influence of metal plasticity and specimen size on ARALL Laminate notched panels residual strength. Interpretation of the test data and implications of the findings on ARALL design allowables and damage tolerance assessment are given.

MATERIALS AND EXPERIMENTAL DETAILS

Materials used in this investigation were 3/2 ARALL-1 and 3/2 ARALL-2 Laminates. These materials differ by the aluminum alloy: 7475-T6 is the present metallic constituent of commercial ARALL-1; however, an earlier version of ARALL-1 employing 7075-T6 was used in this study. Alloy 2024-T3 is the metallic constituent of ARALL-2. Of the two laminate metallic constituents, alloy 7075-T6 (ARALL-1) possesses highest strength, while toughness and ductility is greater for 2024-T3 (ARALL-2), see Figure 2. The prepreg system used in both ARALL Laminate variants is the same. In commercial ARALL-1 Laminate the post cure metal layer tension residual stresses are reversed to compression by a prestretching procedure (commercial ARALL-2 Laminates are not stretched). In this investigation both ARALL-1 and ARALL-2 were considered in the unstretched condition. Other details of the manufacturing procedures and material properties can be found in [1].

The specimens used in this investigation were Center Cut Tension (CCT) panels shown in Figure 3. The sawcuts were introduced by jeweler saw, 0.3 mm thick. The CCT specimens were tested in an INSTRON screw driven testing machine. The residual strength test results are shown in Figure 3.

As can be seen from Figure 3, ARALL-1 Laminates (7075-T6 based) exhibit higher notched panel residual strength than ARALL-2 (2024-T3 based) for smaller panel widths and notch sizes. As the notch size and panel width increases the residual strength of ARALL-2 approaches and finally exceeds the residual strength of ARALL-1. This behavior is consistent with the relative ranking of strength and fracture toughness of the two constituent alloys (see Figure 2).

FINITE ELEMENT ANALYSIS RESULTS

In order to investigate the observed residual strength behavior, a finite element analysis was performed for several specimen geometries. A typical finite element mesh is shown in Figure 4. Material thermal and elastic properties of aramid/epoxy and aluminum, used in the analysis, are given in Table 1. Residual stresses due to the curing process were calculated by a thermal analysis. Maximum applied loads in the analysis were the experimental failure loads for the given specimen geometry.

The finite element results reveal the extent of metal layer plasticity in the ARALL CCT specimens at failure loads. The metal plastic zone boundaries are schematically shown in Figure 3. Apparently, when the notch size is small, both, the ARALL-1 and ARALL-2 specimens fail when the metal layer has yielded in the total specimen uncracked ligament area. As the notch size increases, the laminates exhibit different response. ARALL-1 (7075-T6 based) specimens fail when the crack tip plastic zone is relatively small, and residual strength values drop significantly with increasing notch size. This behavior is similar to the response of CCT metal specimens when the residual strength is determined by Linear Elastic Fracture Mechanics (LEFM).

The ARALL-2 (2024-T3 based) Laminates, on the other hand, fail when the aluminum layer yields in the net section for all shown values of panel width and notch sizes. The more ductile ARALL-2 behavior can be explained by the higher ductility and lower yield stress of 2024-T3 contrasted to higher strength 7075-T6 in ARALL-1. The residual strength in this case also decreases as the notch size increases, but the reduction is less severe than for ARALL-1. This observation is similar to monolithic metal CCT panel behavior when residual strength is determined by the net section criterion [2]. For ARALL Laminates this criterion will be called Modified Net Section (MNS), because while the aluminum yields in the uncracked ligament, the fiber layer is still elastic, and it is not failing in the net section. The final failure in this case occurs when the notch tip fiber tensile strain (stress) reaches its critical value.

The experimental data and finite element results suggest that there are two different modes of fracture when the ARALL CCT specimens are tested for residual strength. For small notch sizes and panel width the residual strength is determined by the MNS criterion, while for larger notch sizes and panel width the governing criterion is LEFM. For the 7075-T6 based ARALL-1 Laminates, the transition from one mode to another is seen in Figure 3. To determine this MNS to LEFM fracture mode transition for ARALL-2 Laminates, larger notches and wider panels were tested. The test results are shown in Figure 5. The finite element analysis, performed for the tested specimen geometries, reveals the extent of the metal layer plastic zone at the failure loads. These results are schematically shown in Figure 5. As can be seen from this figure, when the specimen panel width is small, extensive yielding of the metal layer net section occurs, and the residual strength is determined by MNS. For large notches and panel widths, the plastic zone is constrained at the notch tip, and the residual strength response is governed by LEFM. These findings suggest that for damage tolerance assessment of 2024-T3 based ARALL-2 Laminates large notches and panel widths should be tested. The 7075-T6 based ARALL-1 Laminates show similar specimen size effect, but the LEFM response is valid at much smaller panel widths (see Figure 3).

DISCUSSION

The difference in the observed residual strength behavior of ARALL-1 and-2 Laminates and the specimen size effects can be explained by considering the MNS and LEFM fracture modes. When the notch size and panel width are small, the residual strength of ARALL Laminates is determined by the MNS criterion, and the increase in the aluminum yield stress results in higher laminate residual strength. For that reason residual strength of 7075-T6 (high strength) based ARALL-1 is greater than that of 2024-T3 based ARALL-2.

As the notch size and panel width increases, the transition from MNS to LEFM mode takes place. The experimental results show that for large panel widths, when the notch tip damage zone is small relative to the panel dimensions, the residual strength of 2024-T3 (high toughness) based ARALL-2 Laminates exceeds that of

7075-T6 based ARALL-1. The laminate residual strength response in this case is controlled by some effective laminate fracture toughness. This effective fracture toughness is determined by the laminate critical energy release rate, which can be computed by rule of mixtures if the aluminum fracture toughness and fiber layer strength are known, as described in [4]. Therefore, the increase in metallic constituent fracture toughness will result in higher laminate residual strength for panel widths and notch sizes sufficiently large for the LEFM criterion to be dominant.

These findings have significant implications on such important issues for aircraft applications as notched strength design allowables and material damage tolerance assessment. The residual strength of small width panels used for determining notch strength design allowables is shown to be governed by the fiber stiffness and strength and the yield stress of the metal layer. The extrapolation of the small coupon test data to the material damage tolerance assessment for wide panels can lead to erroneous results if the fracture mode transition (MNS to LEFM) occurs with the panel width increase. Residual strength in this case is controlled by the fracture toughness of the laminate, and, for a given fiber/epoxy system, it is the increase in the metal fracture toughness that leads to improvement in laminate damage tolerance.

CONCLUSIONS

As a result of this investigation, the following conclusions are reached:

1. For small notches and panel width, residual strength of 7075-T6 based ARALL-1 Laminate is higher than that of 2024-T3 based ARALL-2. In this case, for a given fiber/epoxy system, the aluminum yield stress controls the laminate residual strength, and 7075-T6 aluminum alloy with higher yield strength produces higher ARALL Laminate residual strength.

2. For larger notches and panel widths, ARALL-2 Laminate residual strength exceeds that one of ARALL-1. In this case the scale of notch tip yielding is small with respect to panel size, and, the more tough 2024-T3 aluminum alloy increases ARALL Laminate fracture toughness, and consequently laminate residual strength.

3. The small coupon residual strength test is relevant to the establishment of notch strength design allowables. For damage tolerance assessment, however, large notches and panel widths should be tested. Because of the higher ductility and fracture toughness of 2024-T3 over that of 7075-T6, valid damage tolerance assessment requires a larger panel width for ARALL-2 Laminates than for ARALL-1.

REFERENCES

1. R.J. Bucci, L.N. Mueller, L.B. Vogelesang, J.W. Gunnink, "ARALL® Laminates", Aluminum Alloys- Contemporary Research and Applications, A.K. Vasudevan and R.D. Doherty, Eds., Treatise on Material Science and Technology, Vol. 31, Academic Press Inc., San Diego, 1989, pp. 295-322.
2. C.E. Feddersen, "Evaluation and Prediction of the Residual Strength of Center Crack Tension Panels", ASTM STP 486, 1971, pp.16-38.
3. J. Awerbuch, M.S. Maducar, J. of Reinforced Plastics and Composites, Vol. 4, 1985, pp. 3-146.
4. J. Macheret, R.J. Bucci, M. Kulak, "Residual Strength Prediction of ARALL® Laminates Panels with Cracks and Cutouts", ALCOA Tech. Report, in preparation.

Table 1. Material Properties of Aramid/Epoxy and Aluminum Used in the Finite Element Analysis

Material	Transverce Modulus* E_1, 10^6 Mpa	Longitudinal Modulus*, E_2, 10^6 Mpa	Poisson's Ratio* ,ν_{12}	In-plane Shear Modulus* G_{12}, 10^6 Mpa	Out-of-Plane Shear Modulus*, G_{23}, 10^6 Mpa	Thermal Expansion Coefficient* 10^{-6}/°C	
						transv.	longit.
Aramid/ Epoxy	0.66	9.0	0.026	0.236	0.222	70.0	-0.6
7075-T6, 2024-T3	10.4	10.4	.3	4.0	4.0	23.0	23.0

* "1" and "2" denote direction perpendicular to and along the fibers, respectively

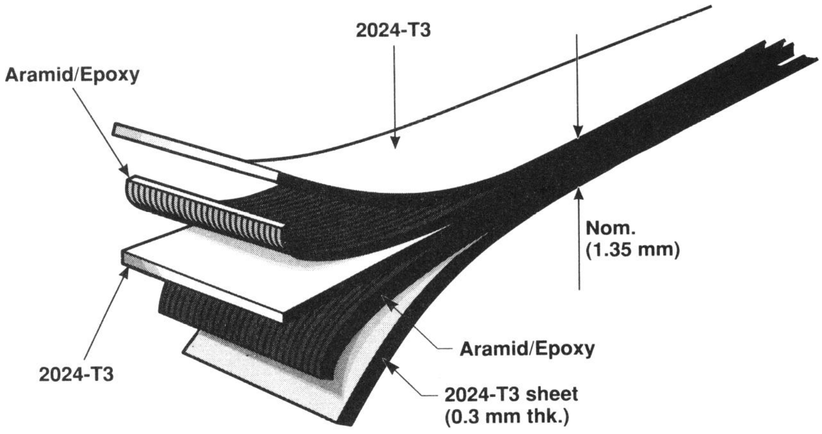
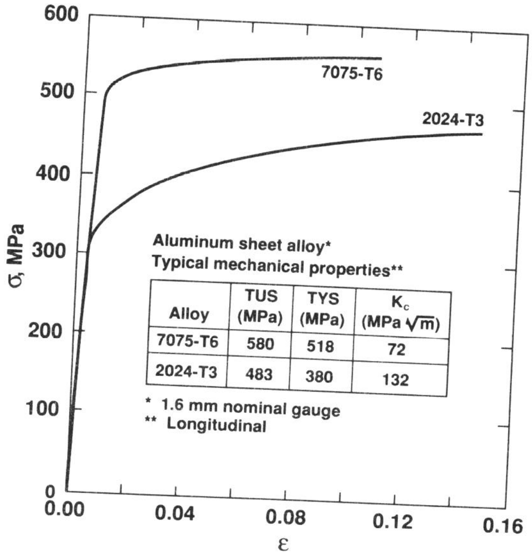
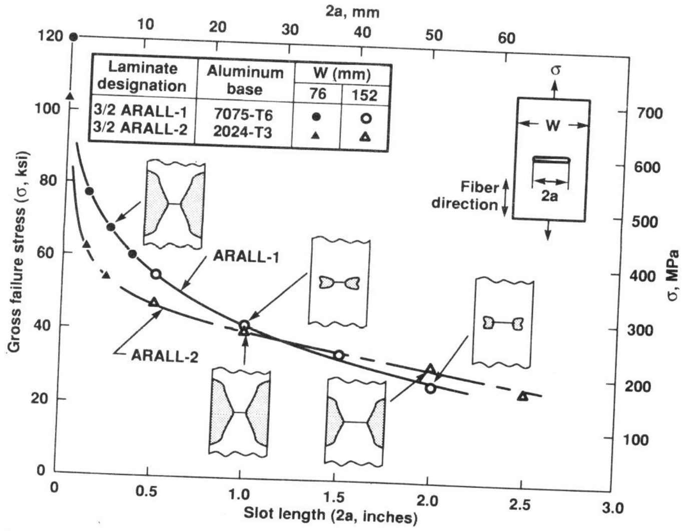


Figure 1: Schematic Representation of 3/2 ARALL® -2 Laminate



Alloy	TUS (MPa)	TYS (MPa)	K_c (MPa $\sqrt{m}$)
7075-T6	580	518	72
2024-T3	483	380	132

Figure 2: Elasto-Plastic Response of 7075-T6 and 2024-T3 Aluminum Sheet Alloys Used in the Finite Element Analysis



Laminate designation	Aluminum base	W (mm)	
		76	152
3/2 ARALL-1	7075-T6	●	○
3/2 ARALL-2	2024-T3	▲	△

Figure 3: Effect of Aluminum Yield Strength on ARALL® Laminate Residual Strength Failure Mode Transition. Shaded Areas Schematically Represent Elasto-Plastic Metal Boundaries.

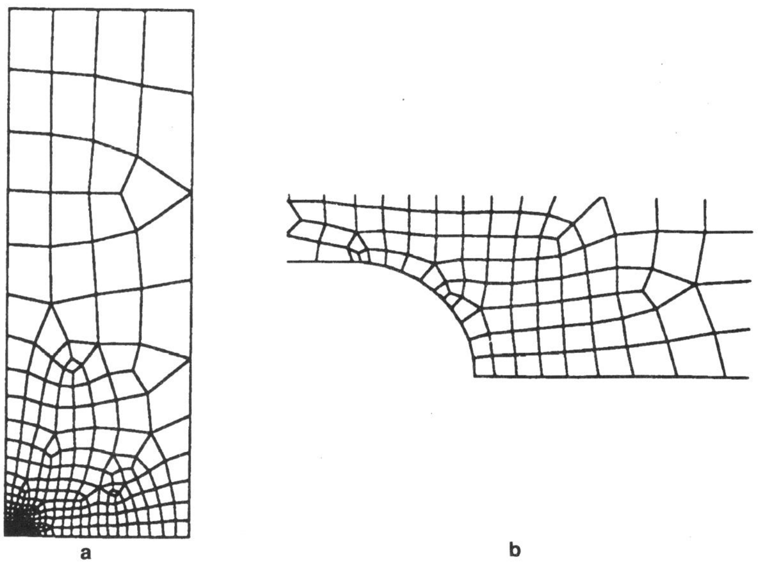


Figure 4: A Typical Finite Element Mesh (a) and the Crack Tip Detail (b) of a Center Cut Tension Specimen, W = 76 mm, 2a = 25.4 mm

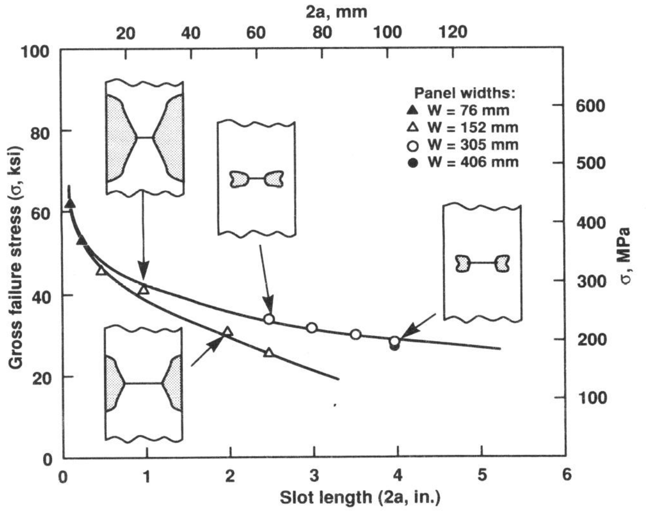


Figure 5: Specimen Size Effects on ARALL® Laminate Residual Strength Failure Modes. Shaded Areas Schematically Represent Elasto-Plastic Metal Layer Boundaries.