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Link-Up Strength of 2524-T3 and 2024-T3 Aluminum Panels with Multiple Site Damage

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The aluminum alloy 2524-T3 is replacing 2024-T3 for many applications because 2524-T3 has a greater fracture toughness while retaining the same strength. Much attention has been given to the effect of multiple site damage on 2024-T3 aluminum; however, very little has been reported about 2524-T3. Twenty-two panels of 2524-T3, each with a different crack configuration, were tested for critical (linkup) strength, and the results were compared with an identical set of previously tested 2024-T3 panels with MSD. The panels were 24 in. wide with a midspan row of 0.25-in.-diam holes at 1-in. pitch. Each panel had a central lead crack with collinear MSD cracks emerging from both sides of the adjacent holes. A comparison of the results showed the 2524-T3 panels to average approximately 27% greater strength than the 2024-T3 panels. The linkup or plastic-zone-touch model used to predict the critical (link-up) strength of the panels was found to be highly conservative. Consequently the test data were used for a semi-empirical analysis to develop a modified link-up model for 2524-T3, similar to the one previously developed for 2024-T3. The average error between the critical strengths from testing and those predicted by the link-up model was approximately 20%, whereas that for the modified link-up model was approximately 3%.

Nomenclature

a	=	lead crack half-length
a_n	=	nominal lead crack half-length
c	=	multiple-site-damage (MSD) crack length
D	=	hole diameter
L	=	longitudinal grain direction (MIL-HDBK-5G); ligament length
LT	=	long transverse grain direction (MIL-HDBK-5G)
ℓ	=	half-length for MSD crack and hole, $c + D/2$
P_{test}	=	load for ligament failure based on testing
R_a	=	ratio of the 2524-T3 modified link-up strength to the 2024-T3 modified link-up strength when A-Basis yield strength is used
R_{anew}	=	ratio of the 2524-T3 modified link-up strength to the new 2024-T3 modified link-up strength when A-Basis yield strength is used
R_b	=	ratio of the 2524-T3 modified link-up strength to the 2024-T3 modified link-up strength when B-Basis yield strength is used
R_{bnew}	=	ratio of the 2524-T3 modified link-up strength to the new 2024-T3 modified link-up strength when B-Basis yield strength is used
R_t	=	ratio of 2524-T3 critical strength to 2024-T3 critical strength based on test values
t	=	panel thickness
w	=	panel width
β_a	=	correction to stress intensity of the lead crack, $\beta_{a/\ell}\beta_w$
$\beta_{a/\ell}$	=	correction to stress intensity of the lead crack for the effect of the adjacent MSD crack
β_b	=	correction to stress intensity of the adjacent MSD crack for the effect of an open hole
β_ℓ	=	correction to stress intensity of the adjacent MSD crack, $\beta_{\ell/a}\beta_b\sqrt{(c/\ell)}$
$\beta_{\ell/a}$	=	correction to stress intensity of the adjacent MSD crack for the effect of the lead crack
β_w	=	finite-width correction to stress intensity of the lead crack, $\sqrt{[\sec(\pi a/w)]}$
σ	=	remote stress
σ_{bf}	=	critical strength based on brittle fracture
σ_c	=	critical strength for ligament failure
σ_{LU}	=	critical strength for ligament failure based on link up
$\sigma_{\text{LUmod(2024)}}$	=	critical strength for ligament failure based on modified link up for 2024-T3
$\sigma_{\text{LUmod(2024new)}}$	=	critical strength for ligament failure based on the new modified link up for 2024-T3
$\sigma_{\text{LUmod(2524)}}$	=	critical strength for ligament failure based on modified link up for 2524-T3
σ_{nsy}	=	critical strength based on net section yielding
σ_{test}	=	critical strength for ligament failure based on testing, P_{test}/wt
σ_{ys}	=	yield strength

Introduction

MULTIPLE site damage (MSD), which is small-scale cracking from fatigue loading, occurs in aging aircraft. An example of MSD is shown in the schematic diagram in Fig. 1, where the panel has a central lead crack of length $2a$ and collinear MSD cracks emerging from the adjacent holes. A value of the remote stress σ that produces crack extension followed by ligament failure is referred to herein as a critical strength. The critical strength usually cannot be determined by conventional brittle fracture based on fracture toughness or by net-section yielding based on yield strength. Swift[1] described an analytical model called the link-up model or the plastic-zone-touch model that has been used to predict the critical strength of panels with MSD; however, this model does not give accurate results for many configurations. Smith et al.[2] developed modified link-up models based on test data from 40 panels of 2024-T3, each with a different crack configuration. There were three different panel widths and two different panel thicknesses. Some panels were bare, and some were clad. Some panels had the grain running parallel to the load, and some had the grain running perpendicular to the load. Testing was done at three different laboratories. These modified

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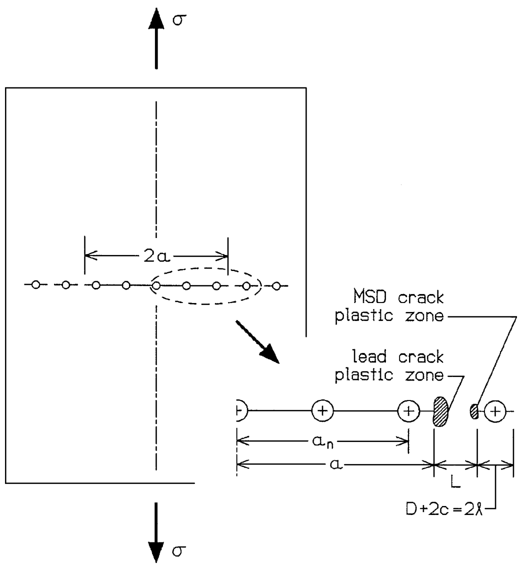

Fig. 1 Schematic diagram of a panel with multiple site damage.

link-up models were subsequently validated with test data from 36 stiffened panels[3] and 36 panels with bolted single lap joints.[4] These models were developed for use with either A-Basis or B-Basis yield strengths. In addition, Smith et al.[5] developed a modified link-up model as well as a correction to a brittle fracture model for 7075-T6 aluminum.

The use of 2524-T3 aluminum has become widespread because it has the same strength properties as 2024-T3, but higher fracture toughness. The purpose of the project described herein was to develop a modified link-up model for 2524-T3 aluminum and to compare the critical (link-up) strength of 2524-T3 with 2024-T3. Twenty-two panels of 2524-T3 aluminum with identical crack configurations as used by Smith et al.[2] for the 2024-T3 material were tested. A modified link-up model for 2524-T3 was developed for use with either A-basis or B-Basis yield strengths. The critical (link-up) strengths of the two alloys were compared, and the 2524-T3 panels were found to have an average strength approximately 27% greater than the 2024-T3 panels.

Link-Up Model

Swift[1] brought attention to an analytical model, known as the link-up model or plastic-zone-touch model, to predict the remote stress that produces ligament failure. The link-up model is given in Eq. (1):

$$\sigma_{\mathrm{LU}} = \sigma_{\mathrm{ys}}\sqrt{\frac{2L}{a\beta_a^2 + \ell\beta_\ell^2}} \tag{1}$$

The corrections to the stress intensity factor of the lead crack and adjacent MSD crack (Fig. 1) are as follows:

Lead crack:

$$\beta_a = \beta_{a/\ell}\beta_w \tag{2}$$

MSD crack:

$$\beta_\ell = \beta_{\ell/a}\beta_b\sqrt{c/\ell} \tag{3}$$

The correction to the stress intensity factor of the lead crack for the effect of the adjacent MSD crack is $\beta_{a/\ell}$ (Ref. 6, p. 118). The quantity β_w is the finite-width correction to the stress intensity factor of the lead crack and is given by $\beta_w = \sqrt{[\sec(\pi a/w)]}$. The correction to the stress intensity factor of the adjacent MSD crack for the effect of the lead crack is $\beta_{\ell/a}$ (Ref. 6, p. 117). The quantity β_b is the correction for open holes,[7] which is given by Eq. (4):

$$\beta_b = 1 - \frac{0.15}{1+2c/D} + \frac{3.46}{(1+2c/D)^2} - \frac{4.47}{(1+2c/D)^3} + \frac{3.52}{(1+2c/D)^4} \tag{4}$$

According to Eq. (1), ligament failure will occur when the remote stress σ (Fig. 1) reaches a level (σ_{LU}) that causes the plastic zones of the lead crack tip and the adjacent MSD crack tip to touch. Previous testing has shown that although the link-up model is accurate for some configurations it is inaccurate for others and is therefore unreliable. Various modified link-up models have since been developed.

Modified Link-Up Model for 2024-T3

The modified link-up model developed by Smith et al.[2] for 2024-T3, which is used to compare the 2524-T3 alloy with the 2024-T3 alloy, is given in Eq. (5):

$$\sigma_{\mathrm{WSU2}} = \sigma_{\mathrm{LUmod(2024)}} = \sigma_{\mathrm{LU}}/[C_1 \ln L + (C_2 + 1)] \tag{5}$$

The quantity σ_{WSU2} is the value of the remote stress σ that will result in ligament failure between the tip of the lead crack and the tip of the adjacent MSD crack. For the remainder of this paper, this quantity will be denoted as $\sigma_{\mathrm{LUmod(2024)}}$. The coefficients in Eq. (5) are $C_1 = 0.3065$ and $C_2 = 0.3123$ when A-Basis yield strength values from MIL-HDBK-5G are used and $C_1 = 0.3054$ and $C_2 = 0.3502$ for B-Basis yield strength values. A nondimensionalized version of Eq. (5) was also developed, but it was found to be slightly less accurate and will not be used herein.

Test Data for the 2524-T3 Panels

Twenty-two panels were cut from two large sheets of 2524-T3 clad aluminum and tested in a servohydraulic testing machine. Figure 2 shows a drawing of a test panel. The panels tested were 24 in. wide, 0.063 in. thick, and 36 in. long between the bolted test fixtures at top and bottom. Each panel had 17 holes with a 1-in. pitch along the horizontal centerline, and each hole was 0.25 in. in diameter. Midspan channel fixtures on each side of the panel prevented out-of-plane displacement along the crack line, and L-shaped stiffeners at top and bottom helped distribute the load uniformly across the width of the panel at each end.

An electrodischarge machine (EDM) produced the man-made lead crack and the MSD cracks in each panel. These cracks were made with a 0.004-in.-diam wire, resulting in 0.005-in. actual man-made crack widths. Twenty-two different crack configurations, which are identical to the 2024-T3 panels tested in Ref. 2, were tested so that a direct comparison could be made between the two materials. Table 1 shows the different panel configurations along with A-Basis and B-Basis yield strength values from MIL-HNBK-5G and the fracture toughness values provided by Alcoa.

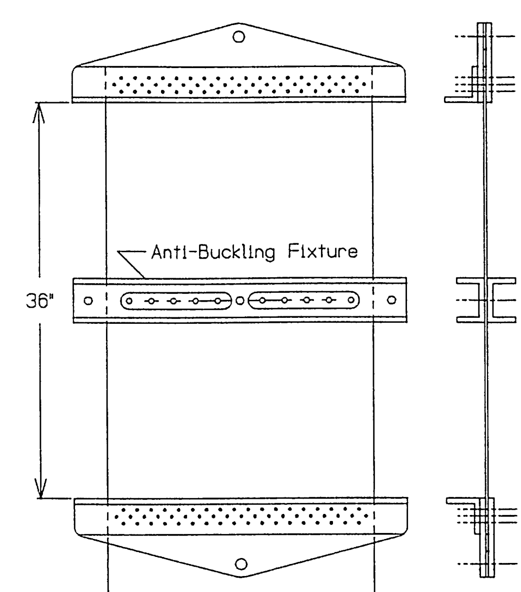

Fig. 2 Front- and side-view schematic diagram of the test setup.

Table 1 Panel configuration and material information ($w = 24$ in., $t = 0.063$ in., $D = 0.25$ in.)

Panel id	*Load direction	a, in.	c, in.	L, in.	A-basis σ_{ys}, ksi	B-basis σ_{ys}, ksi	K_c, ksi*in.$^{1/2}$
1	L	3.675	0.05	0.15	45	47	186
2	L	3.575	0.05	0.25	45	47	186
3	L	3.475	0.05	0.35	45	47	186
4	LT	3.325	0.20	0.35	40	42	164
5	LT	3.275	0.15	0.45	40	42	164
6	LT	3.225	0.10	0.55	40	42	164
7	LT	3.175	0.05	0.65	40	42	164
8	LT	4.675	0.05	0.15	40	42	164
9	LT	4.575	0.05	0.25	40	42	164
10	LT	4.475	0.05	0.35	40	42	164
11	LT	4.325	0.20	0.35	40	42	164
12	LT	4.275	0.15	0.45	40	42	164
13	LT	4.225	0.10	0.55	40	42	164
14	LT	4.175	0.05	0.65	40	42	164
15	L	5.675	0.05	0.15	45	47	186
16	L	5.575	0.05	0.25	45	47	186
17	L	5.475	0.05	0.35	45	47	186
18	LT	5.325	0.20	0.35	40	42	164
19	LT	5.275	0.15	0.45	40	42	164
20	LT	5.225	0.10	0.55	40	42	164
21	LT	5.175	0.05	0.65	40	42	164
22	LT	6.325	0.20	0.35	40	42	164

Table 2 Raw test data and critical strength values for 2524-T3 and 2024-T3

Panel id	$P_{test(2024)}$	$P_{test(2524)}$	P_{test}, % diff	$\sigma_{test(2024)}$	$\sigma_{test(2524)}$
1	17.51	22.40	27.90	11.58	14.81
2	21.30	27.23	27.84	14.09	18.01
3	24.60	30.64	24.55	16.27	20.26
4	20.67	27.50	33.04	13.67	18.19
5	24.13	31.62	31.04	15.96	20.91
6	26.32	34.28	30.24	17.41	22.67
7	29.06	37.82	30.14	19.22	25.01
8	14.82	19.52	31.68	9.80	12.91
9	18.28	23.48	28.45	12.09	15.53
10	20.82	26.52	27.38	13.77	17.54
11	18.05	23.83	32.02	11.94	15.76
12	21.30	27.26	27.98	14.09	18.03
13	23.18	29.99	29.38	15.33	19.83
14	26.26	32.92	25.36	17.37	21.77
15	12.94	16.99	31.30	8.56	11.24
16	16.22	20.57	26.82	10.73	13.60
17	18.36	22.62	23.18	12.14	14.96
18	15.62	20.24	29.58	10.33	13.39
19	18.31	23.60	28.89	12.11	15.61
20	20.59	25.65	24.58	13.62	16.96
21	23.84	28.33	18.83	15.77	18.74
22	15.62	17.69	13.25	10.33	11.70
Average	——	——	27.43	——	——

To match the test procedure used in Ref. 2 for the 2024-T3 panels, stroke control was used at a rate of 0.01 in. per minute until the ligament failed. Real-time observations were made with a closed-circuit television, which magnified one side of the lead crack and adjacent MSD crack. A charge-coupled device camera and S-VHS video recorder were used to record the test results. A time code generator imprinted a time reference on the video every 1/30 of a second, and a video mixer and video camera were used to imprint the load values. This allowed frame-by-frame viewing of the recorded images and the load vs time measurements. Table 2 contains the test data for each of the 22 panels for both the 2024-T3 alloy and the 2524-T3 alloy and the percent difference, which is the difference divided by the value for 2024-T3 then multiplied by 100.

There has been a concern as to whether crack tips produced by EDM or saw cut can be used to produce reliable results for residual strength tests, as compared with results produced from fatigue cracked specimens. Although this concern was addressed in Ref. 2, it is of little consequence here, because the major objective is to compare the link-up strength of 2024-T3 with that of 2524-T3. The most important thing is that the testing be identical for the two materials.

Modified Link-Up Model for 2524-T3

The link-up model, Eq. (1), predicts conservative critical strength values for all panel configurations (Table 3), with an average difference between σ_{test} values and σ_{LU} values of 22.81%. The percent error is defined as the absolute value of the difference between the test value and the value predicted by the link-up equation divided by the test value and multiplied by 100. The same empirical approach was used to develop the modified link-up model for 2524-T3 as was used by Smith et al.[2] to develop the modified linkup model for 2024-T3 given in Eq. (5). Because the ligament length L strongly influences the link-up strength σ_{LU}, the data were displayed as shown in Fig. 3 when A-Basis yield strengths are used. A similar figure, not shown herein, is obtained when B-Basis yield strengths are used. The ligament length is plotted on the horizontal axis, and the difference between the linkup strength σ_{LU} and the test value σ_{test} divided by the test value σ_{test} is plotted on the vertical axis. Although some scatter exists in the test data, a reasonably good representation of the data can be made with a single equation of the natural log form. When the data are represented by a single curve, the stress σ_{test} becomes the critical strength, and the modified link-up equation is as

Table 3 2425-T3 critical strengths based on the link-up and modified link-up models for A-basis

Panel id	σ_{test}	σ_{LU}	σ_{LUmod}	σ_{LU}, % error	σ_{LUmod}, % error
1	14.81	9.19	15.14	37.95	2.24
2	18.01	13.18	18.72	26.82	3.92
3	20.26	16.54	21.53	18.38	6.23
4	18.19	13.89	18.08	23.63	0.60
5	20.91	16.86	20.66	19.38	1.22
6	22.67	19.56	22.89	13.73	0.97
7	25.01	22.39	25.26	10.49	1.00
8	12.91	7.17	11.81	44.45	8.47
9	15.53	10.14	14.40	34.70	7.28
10	17.54	12.64	16.45	27.93	6.20
11	15.76	11.92	15.51	24.37	1.56
12	18.03	14.45	17.70	19.85	1.80
13	19.83	16.75	19.60	15.55	1.16
14	21.77	19.05	21.50	12.50	1.27
15	11.24	7.02	11.57	37.53	2.94
16	13.60	9.93	14.10	27.01	3.65
17	14.96	12.39	16.13	17.16	7.82
18	13.39	10.40	13.54	22.31	1.12
19	15.61	12.58	15.41	19.40	1.25
20	16.96	14.47	16.94	14.70	0.17
21	18.74	16.47	18.58	12.10	0.81
22	11.70	9.14	11.90	21.88	1.68
Average	——	——	——	22.81	2.88

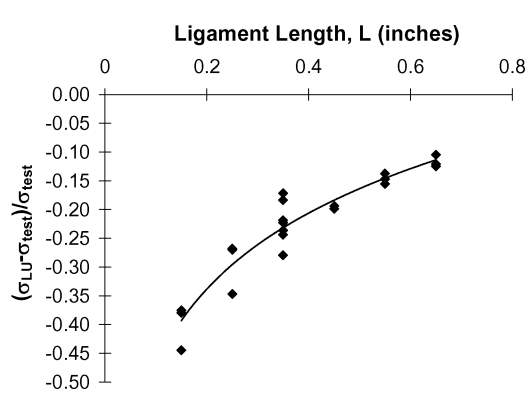

Fig. 3 Natural log form correction for 2524-T3 (for A-basis yield strength).

follows:

$$(\sigma_{\mathrm{LU}} - \sigma_c)/\sigma_c = C_1 \ln L + C_2 \tag{6}$$

or

$$\sigma_c = \sigma_{\mathrm{LUmod(2524)}} = \sigma_{\mathrm{LU}}/[C_1 \ln L + (C_2 + 1)] \tag{7}$$

The coefficients in Eq. (7) are $C_1 = 0.1905$ and $C_2 = -0.0317$ when A-Basis yield strength values are used, and when B-Basis yield strengths are used the coefficients are $C_1 = 0.2024$ and $C_2 = 0.0719$.

Results

The raw test data P_{test} and the corresponding critical strength values σ_{test} for 2524-T3 and 2024-T3 are given in Table 2. The 2524-T3 alloy carried, on average, approximately 27% greater load than the 2024-T3 alloy. Most of the 2524-T3 panels carried at least 23% more load than the 2024-T3 panels, with panels 21 and 22 being the only exceptions. The critical strengths for 2524-T3 predicted by both the link-up equation and the modified link-up equation are given in Table 3 when A-Basis yield strengths are used and Table 4 for B-Basis yield strengths. The percent error, as defined earlier, between the analytical model and the test value is also given for each panel. The critical strengths from testing and from both the link-up model and the modified link-up model are shown in Fig. 4 when A-Basis yield strengths are used. The figure for B-Basis yiels strengths is not shown because it is similar.

The critical strength values of 2524-T3 and 2024-T3 for A-basis and B-basis yield strengths based on the modified link-up models are given in Table 5. Table 5 also gives the percent difference between the two alloys for each of the panels. These data are presented graphically in Fig. 5 for A-Basis yield strengths. B-Basis yield strengths results are similar.

Table 4 2425-T3 critical strengths based on the link-up and modified link-up models for B-basis

Panel id	σ_{test}	σ_{LU}	σ_{LUmod}	σ_{LU}, % error	σ_{LUmod}, % error
1	14.81	9.59	15.13	35.25	2.14
2	18.01	13.77	18.68	23.54	3.70
3	20.26	17.27	21.44	14.78	5.81
4	18.19	14.59	18.11	19.78	0.40
5	20.91	17.70	20.67	15.36	1.16
6	22.67	20.53	22.89	9.45	0.96
7	25.01	23.51	25.26	6.01	0.99
8	12.91	7.52	11.86	41.74	8.09
9	15.53	10.65	14.44	31.42	6.99
10	17.54	13.27	16.48	24.34	6.06
11	15.76	12.52	15.54	20.56	1.37
12	18.03	15.17	17.72	15.86	1.74
13	19.83	17.59	19.61	11.32	1.12
14	21.77	20.00	21.49	8.14	1.30
15	11.24	7.33	11.56	34.77	2.90
16	13.60	10.37	14.06	23.78	3.38
17	14.96	12.94	16.07	13.49	7.42
18	13.39	10.92	13.56	18.42	1.28
19	15.61	13.20	15.42	15.43	1.24
20	16.96	15.20	16.95	10.40	0.10
21	18.74	17.30	18.59	7.67	0.79
22	11.70	9.59	11.91	18.03	1.77
Average	——	——	——	19.07	2.76

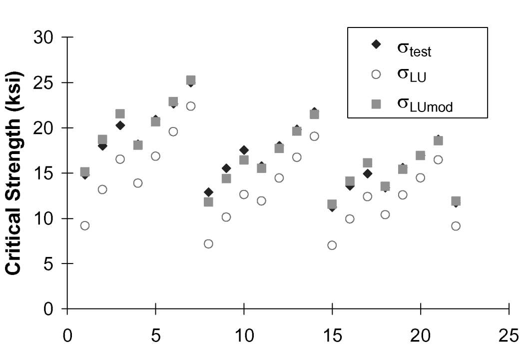

Fig. 4 2524-T3 test strengths compared to the link-up and modified link-up model (for A-basis yield strengths).

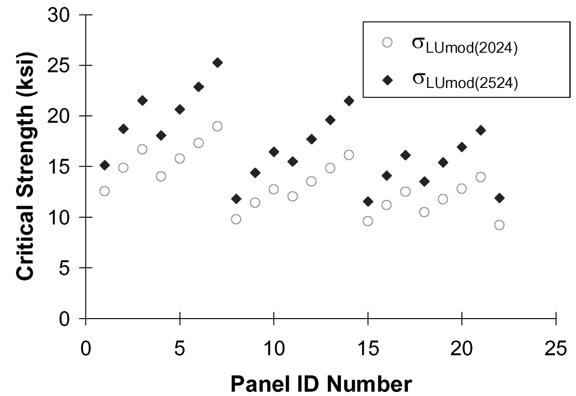

Fig. 5 2524-T3 and 2024-T3 modified link-up panel strengths (for A-basis yield strengths).

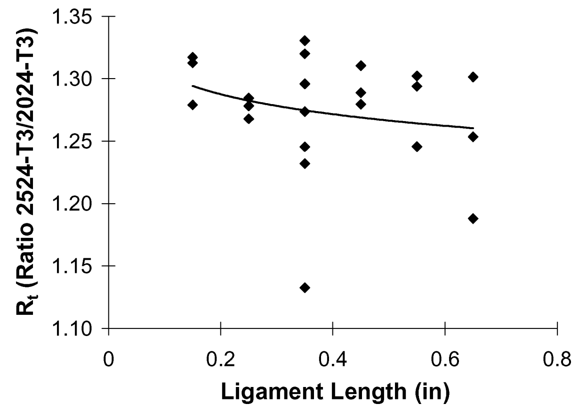

Fig. 6 Ratio of the 2524-T3 critical strength to the 2024-T3 critical strength based on test values.

A ratio of the strength of 2524-T3 to that of 2024-T3 was calculated for the various ligament lengths. Actually, three ratios were determined: one based on the test values, one based on the modified link-up models for A-Basis yield strengths, and one based on the modified link-up models for B-Basis yield strength. These ratios are defined by Eqs. (8) and (9) as follows:

$$R_t = \frac{\sigma_{\mathrm{test(2524)}}}{\sigma_{\mathrm{test(2024)}}} \tag{8}$$

$$R_{a,b} = \frac{\sigma_{\mathrm{LUmod(2524)}}}{\sigma_{\mathrm{LUmod(2024)}}} = \frac{[C_1 \ln L + (C_2 + 1)]_{2024}}{[C_1 \ln L + (C_2 + 1)]_{2524}} \tag{9}$$

When A-Basis yields strengths are used in Eqs. (5) and (7), the ratio is denoted as R_a, and when B-Basis yield strengths are used the ratio is denoted by R_b. These ratios are given in Tables 6 and 7 for each panel and shown graphically in Figs. 6 and 7.

The modified link-up model for 2024-T3 was developed from test data from 40 panels.[2] Twenty-two of these were tested at Wichita State University (WSU), whereas the remaining 18 panels were tested at other locations. During this investigation, a second (or new) modified link-up model for 2024-T3 was developed from just the 22 panels tested at WSU to provide a more direct comparison between the critical strengths of the two materials. The new modified link-up model for 2024-T3 was developed in the same manner as the original modified link-up model for 2024-T3 and the modified link-up model described herein for 2524-T3. Figure 8 shows the new curve fit when A-basis yield strength is used. The figure for B-basis yield strengths is not shown because it is similar. The equation remains the same as Eq. (5); however, the new coefficients are $C_1 = 0.2273$ and $C_2 = 0.2167$ when A-basis yield strengths are used and $C_1 = 0.2417$ and $C_2 = 0.2791$ for B-basis yield strength

Table 5 2524-T3 and 2024-T3 critical strengths based on the modified link-up models for A-basis and B-basis

Panel id	$\sigma_{\mathrm{LUmod}(2024)}$ A-basis	$\sigma_{\mathrm{LUmod}(2524)}$ A-basis	Percent difference	$\sigma_{\mathrm{LUmod}(2024)}$ B-basis	$\sigma_{\mathrm{LUmod}(2524)}$ B-basis	Percent difference
1	12.57	15.14	20.47	12.45	15.13	21.51
2	14.86	18.72	25.95	14.86	18.68	25.68
3	16.69	21.53	28.99	16.77	21.44	27.86
4	14.03	18.08	28.86	14.17	18.11	27.84
5	15.79	20.66	30.82	16.00	20.67	29.19
6	17.32	22.89	32.18	17.59	22.89	30.13
7	18.97	25.26	33.18	19.29	25.26	30.95
8	9.80	11.81	20.55	9.76	11.86	21.54
9	11.43	14.40	25.98	11.49	14.44	25.71
10	12.76	16.45	28.93	12.89	16.48	27.82
11	12.04	15.51	28.86	12.16	15.54	27.84
12	13.53	17.70	30.85	13.71	17.72	29.22
13	14.84	19.60	32.10	15.07	19.61	30.14
14	16.14	21.50	33.18	16.41	21.49	30.95
15	9.60	11.57	20.49	9.51	11.56	21.59
16	11.19	14.10	26.01	11.19	14.06	25.69
17	12.51	16.13	28.91	12.57	16.07	27.81
18	10.50	13.54	28.92	10.61	13.56	27.79
19	11.78	15.41	30.84	11.93	15.42	29.22
20	12.82	16.94	32.10	13.01	16.95	30.26
21	13.96	18.58	33.12	14.19	18.59	30.99
22	9.22	11.90	29.03	9.32	11.91	27.76
Average	——	——	28.65	——	——	27.61

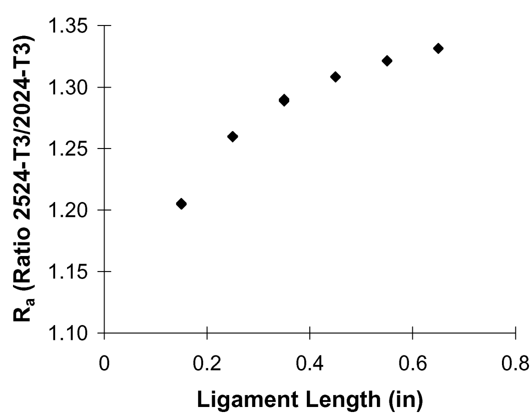

Fig. 7 Ratio of the 2524-T3 modified link-up strength to the 2024-T3 modified link-up strength (for A-basis yield strength).

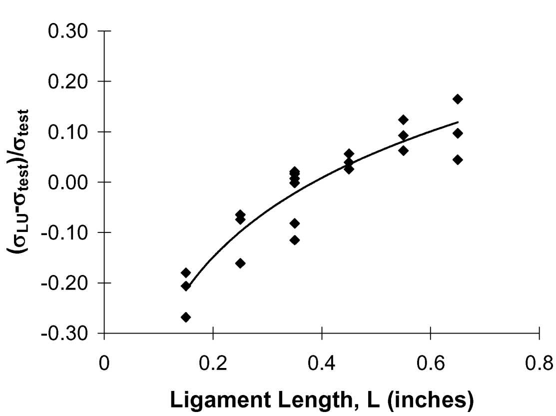

Fig. 8 New natural log form correction for 2024-T3 (for A-basis yield strength).

values. The critical strength for this new modified link-up model is denoted as $\sigma_{\mathrm{LUmod(2024new)}}$. Ratios of critical strengths of 2524-T3 and 2024-T3 based on the new modified link-up models for 2024-T3 A-basis and B-basis yield strengths are denoted by R_{anew} and R_{bnew} and are given in Eq. (10) and Table 8.

$$R_{\mathrm{a,bnew}} = \frac{\sigma_{\mathrm{LUmod(2524)}}}{\sigma_{\mathrm{LUmod(2024new)}}} = \frac{[C_1 \ln L + (C_2 + 1)]_{2024\mathrm{new}}}{[C_1 \ln L + (C_2 + 1)]_{2524}} \tag{10}$$

Table 6 Ratio of the critical strength of 2524-T3 to 2024-T3 (based on panel strengths at failure)

Panel id	L, in.	$\sigma_{\mathrm{test}(2524)}$	$\sigma_{\mathrm{test}(2024)}$	R_t stress
1	0.15	14.81	11.58	1.279
8	0.15	12.91	9.80	1.317
15	0.15	11.24	8.56	1.313
2	0.25	18.01	14.09	1.278
9	0.25	15.53	12.09	1.284
16	0.25	13.60	10.73	1.268
3	0.35	20.26	16.27	1.246
4	0.35	18.19	13.67	1.330
10	0.35	17.54	13.77	1.274
11	0.35	15.76	11.94	1.320
17	0.35	14.96	12.14	1.232
18	0.35	13.39	10.33	1.296
22	0.35	11.70	10.33	1.133
5	0.45	20.91	15.96	1.310
12	0.45	18.03	14.09	1.280
19	0.45	15.61	12.11	1.289
6	0.55	22.67	17.41	1.302
13	0.55	19.83	15.33	1.294
20	0.55	16.96	13.62	1.246
7	0.65	25.01	19.22	1.301
14	0.65	21.77	17.37	1.253
21	0.65	18.74	15.77	1.188

This ratio is shown graphically in Fig. 9 when A-basis yield strengths are used. The figure for B-Basis yield strength is not shown because it is similar.

Previous testing of 2524-T3 with MSD was done by Grandt et al.,[8,9] and the results were compared with 2024-T3 showing 2524-T3 to have a strength of about 10% greater than 2024-T3, as compared with an increase of about 27% reported herein. This considerable difference can be explained by the fact that the Grandt et al.[8,9] tests were done with 16-in.-wide panels resulting in failure modes closer to net-section yielding than to link-up failure modes. If the mode of failure is net section yielding, the two materials should have the same critical strength. From an elementary point of view, there are three possible modes that can produce crack extension and ligament failure: link up, net-section yielding, and brittle fracture. A critical strength can be determined for each mode. The mode of failure will depend on the panel and crack configuration and will occur according to the mode with the lowest strength. Table 9 shows

Table 7 Ratio of the critical strength of 2524-T3 to 2024-T3 (based on the modified link-up models)

Panel id	L, in.	$\sigma_{\mathrm{LUmod(2524)}}$ A-basis	$\sigma_{\mathrm{LUmod(2024)}}$ A-basis	R_a A-basis	$\sigma_{\mathrm{LUmod(2524)}}$ B-basis	$\sigma_{\mathrm{LUmod(2024)}}$ B-basis	R_b B-basis
1	0.15	15.14	12.57	1.205	15.13	12.45	1.215
8	0.15	11.81	9.80	1.206	11.86	9.76	1.215
15	0.15	11.57	9.60	1.205	11.56	9.51	1.216
2	0.25	18.72	14.86	1.259	18.68	14.86	1.257
9	0.25	14.40	11.43	1.260	14.44	11.49	1.257
16	0.25	14.10	11.19	1.260	14.06	11.19	1.257
3	0.35	21.53	16.69	1.290	21.44	16.77	1.279
4	0.35	18.08	14.03	1.289	18.11	14.17	1.278
10	0.35	16.45	12.76	1.289	16.48	12.89	1.278
11	0.35	15.51	12.04	1.289	15.54	12.16	1.278
17	0.35	16.13	12.51	1.289	16.07	12.57	1.278
18	0.35	13.54	10.50	1.289	13.56	10.61	1.278
22	0.35	11.90	9.22	1.290	11.91	9.32	1.278
5	0.45	20.66	15.79	1.308	20.67	16.00	1.292
12	0.45	17.70	13.53	1.309	17.72	13.71	1.292
19	0.45	15.41	11.78	1.308	15.42	11.93	1.292
6	0.55	22.89	17.32	1.322	22.89	17.59	1.301
13	0.55	19.60	14.84	1.321	19.61	15.07	1.301
20	0.55	16.94	12.82	1.321	16.95	13.01	1.303
7	0.65	25.26	18.97	1.332	25.26	19.29	1.310
14	0.65	21.50	16.14	1.332	21.49	16.41	1.310
21	0.65	18.58	13.96	1.331	18.59	14.19	1.310

Table 8 Ratio of the critical strength of 2524-T3 to 2024-T3 (based on panel the 2524-T3 modified link-up model and the 2024-T3 new modified link-up model)

Panel id	L, in.	$\sigma_{\mathrm{LUmod(2524)}}$ A-basis	$\sigma_{\mathrm{LUmod(2024new)}}$ A-basis	R_{anew} A-basis	$\sigma_{\mathrm{LUmod(2524)}}$ B-basis	$\sigma_{\mathrm{LUmod(2024new)}}$ B-basis	R_{bnew} B-basis
1	0.15	15.14	11.70	1.294	15.13	11.69	1.294
8	0.15	11.81	9.13	1.294	11.86	9.16	1.294
15	0.15	11.57	8.94	1.294	11.56	8.93	1.294
2	0.25	18.72	14.62	1.280	18.68	14.59	1.280
9	0.25	14.40	11.25	1.280	14.44	11.28	1.280
16	0.25	14.10	11.01	1.280	14.06	10.98	1.280
3	0.35	21.53	16.91	1.273	21.44	16.84	1.273
4	0.35	18.08	14.20	1.273	18.11	14.23	1.273
10	0.35	16.45	12.92	1.273	16.48	12.94	1.273
11	0.35	15.51	12.19	1.273	15.54	12.21	1.273
17	0.35	16.13	12.67	1.273	16.07	12.62	1.273
18	0.35	13.54	10.63	1.273	13.56	10.65	1.273
22	0.35	11.90	9.34	1.273	11.91	9.35	1.273
5	0.45	20.66	16.29	1.268	20.67	16.30	1.268
12	0.45	17.70	13.96	1.268	17.72	13.97	1.268
19	0.45	15.41	12.15	1.268	15.42	12.15	1.268
6	0.55	22.89	18.10	1.265	22.89	18.09	1.265
13	0.55	19.60	15.50	1.265	19.61	15.50	1.265
20	0.55	16.94	13.39	1.265	16.95	13.40	1.265
7	0.65	25.26	20.01	1.262	25.26	20.01	1.262
14	0.65	21.50	17.03	1.262	21.49	17.02	1.262
21	0.65	18.58	14.72	1.262	18.59	14.72	1.262

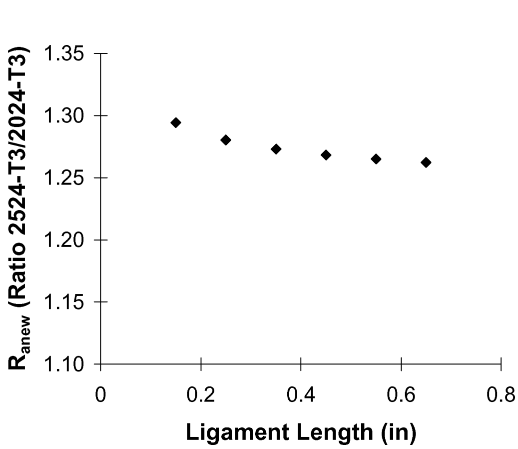

Fig. 9 Ratio of the 2524-T3 modified link-up strength to the new 2024-T3 modified link-up strength (for A-basis yield strength).

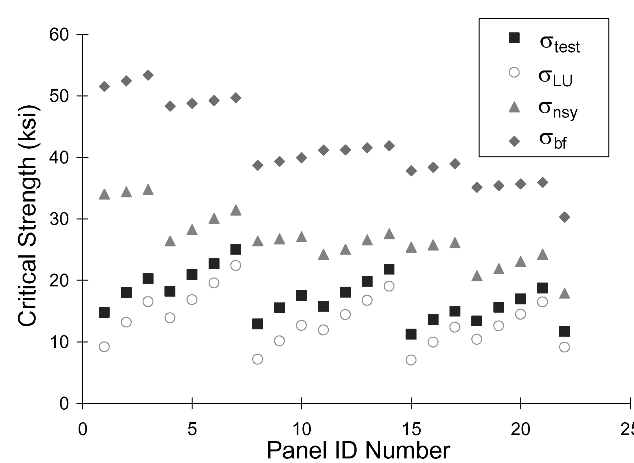

Fig. 10 Critical strengths for the modes of panel failure (link up, net-section yielding, brittle fracture).

Table 9 Critical strengths for the modes of panel failure (link-up, net-section yielding, brittle fracture; A-basis yield strength values used for calculations)

Panel id	σ_{test}	σ_{LU}	σ_{nsy}	σ_{bf}
1	14.81	9.19	34.03	51.56
2	18.01	13.18	34.41	52.45
3	20.26	16.54	34.78	53.37
4	18.19	13.89	26.42	48.33
5	20.91	16.86	28.25	48.78
6	22.67	19.56	30.08	49.22
7	25.01	22.39	31.42	49.68
8	12.91	7.17	26.42	38.73
9	15.53	10.14	26.75	39.33
10	17.54	12.64	27.08	39.94
11	15.76	11.92	24.24	41.18
12	18.03	14.45	25.08	41.21
13	19.83	16.75	26.58	41.54
14	21.77	19.05	27.58	41.87
15	11.24	7.02	25.41	37.82
16	13.60	9.93	25.78	38.39
17	14.96	12.39	26.16	38.96
18	13.39	10.40	20.75	35.12
19	15.61	12.58	21.92	35.39
20	16.96	14.47	23.08	35.65
21	18.74	16.47	24.25	35.92
22	11.70	9.14	17.92	30.27

the critical strengths corresponding to each mode of failure for the panels tested in this paper, and Fig. 10 is a plot of the test values and the three modes of failure vs panel ID number. Table 9 and Fig. 10 show link-up to be the mode of failure for the 22 panels rather than brittle fracture or net-section yielding.

Conclusions

The 2524-T3 and 2024-T3 critical strength values given in Table 2 and Figs. 5 and 6 show that 2524-T3 is on average 27.43% stronger than 2024-T3. Panels 21 and 22 were the only panels that were less than 23% stronger, with panel 21 being nearly 19% stronger and panel 22 being 13% stronger (Table 2). The panel configurations for the two materials were identical, and the testing procedure was the same for all of the panels, which suggests that additional testing should be done to help resolve the inconsistency between the behavior of these two configurations and the others.

A comparison of the test results of the 2524-T3 panels with the link-up model and the modified link-up model shows the average error to be 22.81% for the link-up model and 2.88% for the modified link-up model when A-basis yield strengths are used (Table 3). Table 4 shows the average error to be 19.07% for the link up and 2.76% for the modified link-up model when B-basis yield strengths are used. It is apparent that the 2524-T3 modified link-up model more accurately reflects the test results than the original link-up model for all panel configurations, as shown in Fig. 4. It is also important to compare the critical strength values of 2524-T3 with those for 2024-T3 based on the modified link-up models. The 2524-T3 alloy shows a 28.6% average increase in critical strength over 2024-T3 when A-Basis yield strengths are used and an average increase of 27.6% when B-basis yield strengths are used as shown in Table 5.

A comparison of the strengths of the two alloys vs ligament length gives some interesting results. Figures 6, 7, and 9 show that the critical strength of 2524-T3 is greater than 2024-T3 for all ligament lengths. Inserting a trend line in Fig. 6, however, shows that the 2524-T3 critical strength based on the test values is slightly higher for smaller ligament lengths, whereas the 2524-T3 critical strength based on the modified link-up models for both A-basis (Fig. 7) and B-basis (similar) is the opposite. Not only does the 2524-T3 critical strength increase for larger ligament lengths, it increases significantly compared to the critical strength test value results. Figure 9, which shows the ratio based on the new 2024-T3 modified link-up model, follows a pattern very similar to that of Fig. 6, which is the plot of the ratio of critical strengths based on the test values. Developing the second (or new) modified link-up model for 2024-T3 (based on the 22 configurations rather than 40) allowed for a more direct comparison of 2524-T3 and 2024-T3. This comparison shows that, while the critical strength of 2524-T3 is greater than 2024-T3 for all ligament lengths, it decreases slightly as the ligament length increases. However, the decrease was only about 3% from small to large ligament lengths, which implies that the difference in critical strength between 2024-T3 and 2524-T3 is not strongly influenced by ligament length.

The difference in results between the testing done by Grandt et al.,[8,9] and that done in this paper is worth noting. The Grandt et al.[8,9] test results show a 9–11% improvement in residual strength of 2524-T3 over 2024-T3, whereas the testing done here shows an average increase of 27%. Table 9 and Fig. 10 show the critical strengths for each of three modes of failure for the panels tested in this paper and provide some proof that the panels failed from link up because the critical (link-up) strengths are significantly lower than net-section yield and brittle fracture strengths. The possibility exists that the failure mode of the panels tested by Grandt et al.[8,9] was closer to a net-section yield failure rather than link up because the panels tested were only 16 in. wide, whereas the panels tested in this paper were 24 in. wide. The narrower the panel the more predominant net-section yielding becomes. If the mode of failure is net-section yielding, the two alloys should have the same critical strength.

The 2524-T3 material was designed as a more damage-tolerant alloy to replace 2024-T3, and testing showed that the critical strength of 2524-T3 is on average 27% higher than 2024-T3 for crack configurations under the influence of multiple site damage. The link-up equation developed by Swift[1] can predict the critical strength of 2524-T3, but the results are overly conservative because the equation cannot account for the higher fracture toughness of the alloy. The 2524-T3 modified link-up equation gives considerably better results than the unmodified link-up equation. Although neither stiffened 2524-T3 panels nor bolted joint panels were evaluated, it would be reasonable to assume that the results would be similar because this is a stress intensity based model.

Acknowledgments

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