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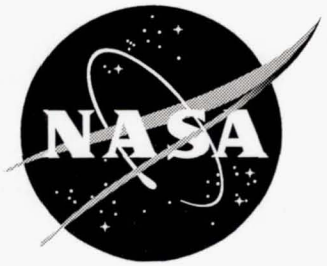

Fracture Tests on Thin Sheet 2024-T3 Aluminum Alloy for Specimens With and Without Anti-Buckling Guides

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March 2001

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Abstract

A series of fracture test were conducted to determine the effects of specimen type, specimen width and buckling on the fracture behavior of cracked thin sheet (0.063 inch thick) 2024-T3 aluminum alloy. A summary of the experimental measurements is presented for fracture tests conducted on two specimen types and various widths. Middle-crack tension M(T) and compact tension C(T) specimens were tested in the L-T and T-L orientation with duplicate tests for each condition. Four widths (W= 3, 12, 24, and 40 inch) were tested for the middle-crack tension specimens, and three widths (W=2, 4, and 6 inch) were tested for the compact tension specimens. The M(T) specimens were tested in either a constrained (out-of-plane displacements restrained with anti-buckling guides) or unconstrained conditions were the specimen was free to buckle out of plane. Measurements were made of load against crack extension for all specimens.

Introduction

Thin sheet 2024-T3 aluminum alloy has been used in commercial aircraft fuselages for the past 50 years. As these commercial aircraft age, it is important to have fracture mechanics models developed to predict failure of the structure subjected to cracking scenarios such as multi-site-damage (MSD) and multi-element-damage (MED). When developing these methodologies it is important to first verify crack growth models on flat aluminum alloy sheets before addressing crack growth in the structure. These tests were designed to demonstrate the effects of specimen type, specimen width, and buckling on the fracture behavior of 0.063 inch thick 2024-T3. This set of fracture test results, along with the tensile stress strain properties, provide the information necessary for analysts to validate fracture mechanics residual strength methodology on this material.

The objective of this paper was to report the experimental measurements made on 0.063 inch thick 2024-T3 aluminum alloy fracture tests. The fracture behavior was characterized through a series fracture tests conducted on compact tension, C(T), and middle crack tension, M(T), specimens. The M(T) specimens were tested with and without anti-buckling guides to provide experimental data on the effects of crack buckling on fracture. The specimens were configured in both the L-T and T-L orientation. To minimize variation due to the material, all specimens were taken from the same lot of aluminum sheet. The test procedures are discussed and the experimental measurements of failure stress, load-against-crack-extension, and the material stress-strain curves are reported.

Experimental Procedure

The fracture behavior of 0.063 inch thick 2024-T3 aluminum alloy was characterized through a series fracture tests on middle crack tension, M(T), and compact tension, C(T), specimens. The M(T) specimens were tested with and without anti-buckling guides to provide experimental data on the

effects of crack buckling on fracture. All C(T) specimens were tested with guide plates and did not experience buckling. The specimens were configured in both the L-T and T-L orientation. The L-T orientation is defined by orientating the crack perpendicular to the rolling direction and load parallel to the rolling direction while the T-L orientation is defined as by orientating the crack parallel to the rolling direction and load perpendicular to the rolling direction. A schematic of a C(T) specimen is shown in Figure 1. Three different C(T) specimen widths were tested: W = 2, 4, and 6 inches. The initial crack-length-to-width ratio was approximately a/W = 0.4 for all of the C(T) specimens. A schematic of a M(T) specimen is shown in Figure 2. Four widths of M(T) specimens (W = 3, 12, 24, and 40 inches) were tested. For the M(T) specimens, the initial crack length-to-width ratio tested was generally 2a/W = 1/3, but the 40-inch wide M(T) specimens were tested at both a 2a/W ratio of 1/5 and 1/3. Experimental measurements of load and crack extension were made during the fracture tests.

The M(T) and C(T) specimens were fatigue precracked at a stress-intensity factor range of about $\Delta K = 8 \text{ ksi}\sqrt{\text{inch}}$ at a stress ratio (minimum to maximum load) between 0.2 and 0.1. The specimens were fractured under displacement control, at a ramp rate in the range of 0.01-0.04 inch/minute. The maximum load achieved in each test was recorded and crack extension was measured using an optical microscope.

Tensile tests were conducted on standard 0.5-inch wide rectangular tension specimens as shown in Figure 3. Specimens were tested in the L and the T directions (rolling direction and long transverse direction respectively). Three specimens were tested for each orientation. The tensile tests were conducted according to the ASTM E8 standard. Young's modulus, yield stress and ultimate tensile strength were determined from the results. A piecewise linear function was fit to the data.

Experimental Results

The maximum load measured in the C(T) tests for both L-T and T-L orientation are listed in Tables 1 and 2, respectively. The L-T C(T) specimens either failed in a slant fracture or a V-fracture, as shown schematically in Figure 4. The failure loads for the V-fracture specimens were higher than similar specimens which fail by slant fracture. The failure loads for the C(T) specimens along with fracture mode are shown in Figure 5. The maximum (failure) stresses calculated from the M(T) test results for both L-T and T-L orientation are listed in Tables 3 and 4, respectively, and are plotted in Figures 6. Results are shown for both the constrained and unconstrained test conditions. The following sections describe the crack length measurements made for each of the specimen types.

Compact Tension Tests

Optical measurements of crack extension at the surface and the corresponding applied load were recorded for each of the C(T) tests. The crack extension measurements were made on one surface of the specimens. The measurements for the L-T orientated specimens are listed in Tables 5-9 and, the measurements for the T-L orientated specimens are listed in Tables 9-11. The load-against-crack extension response of the two orientations is compared for the 2, 4, and 6 inch C(T) specimens in Figures 7, 8, and 9, respectively.

Middle Crack Tension Tests

The experimental setup generally allowed crack extension to be measured at both crack tips. The crack extension (Δa) results reported for the panels represent both crack extensions when two columns of data are present. When the 3 inch M(T) specimens were tested the total front crack length (2a) was recorded. The stresses reported are nominal gross stress in the M(T) specimens and is defined by:

$$\sigma = \frac{F}{W \cdot B} \tag{1}$$

where F is the applied load, W is width and B is thickness. The results for M(T) specimens with a L-T orientation are listed in Tables 12-20 and the results for the specimens with a T-L orientation are listed in Tables 21-25. The load-against-crack extension response of the two orientations is compared for the 3 inch M(T) specimens in Figures 10. The load-crack extension trends are compared for the constrained and unconstrained (buckling) M(T) specimens in Figures 11-16. The results from the 12 inch M(T) specimens for the L-T and T-L orientations are shown in Figures 10 and 11, respectively. The results from the 24 inch M(T) specimens for the L-T and T-L orientations are shown in Figures 13 and 14, respectively. Test Data from the 40-inch wide M(T) specimens is shown for both crack length to width ratios, 2a/W = 1/5 and 2a/W = 1/3 in figures 15 and 16 respectively.

Tension Tests

The results from the tensile tests are presented in Figure 17. This figure shows the stress-strain results from the three tensile tests in each orientation along with a piecewise linear fit to the data. Tabulated values for both linear fits is shown in the two sets of data on Figure 17.

Summary

Fracture and tensile tests were conducted on a thin sheet 2024-T3 aluminum alloy. Both middle crack tension M(T) and compact tension C(T) specimens were tested in the L-T and T-L orientation. Four widths (W= 3, 12, 24, and 40 inch) were tested for the middle crack tension specimens, and three widths (W=2, 4, and 6 inch) were tested for the compact tension specimens. The M(T) specimens were tested in an constrained (no out of plane displacement) and a unconstrained condition where the specimen was free to buckle out of plane. Results in the form of load-against-crack extension and stress-strain behavior were reported.

Table 1. Failure Loads for the C(T) LT Fracture Tests (B = 0.063)

Width (inch)	Crack Length a (inch)	Failure Load (lbs)
2.0	.800	705
2.0	.800	709
2.0	.800	718
4.0	1.600	1314*
4.0	1.600	1261
4.0	1.600	1275
6.0	2.400	1843*
6.0	2.400	1737
6.0	2.400	1735
6.0	2.400	1749
6.0	2.400	1729

* V fracture

Table 2. Failure Loads for the C(T) TL Fracture Tests (B=0.063)

Width (inch)	Crack Length a (inch)	Failure Load (lbs)
2.0	.701	785
2.0	.800	692
2.0	.800	666
4.0	1.600	1187
4.0	1.600	1168
4.0	1.600	1169
6.0	2.400	1600
6.0	2.400	1626
6.0	2.400	1626

Table 3. Failure Stress for the M(T) LT Fracture Tests (B=0.063)

	M(T) LT constrained		M(T) LT unconstrained	
Width (inch)	Fail Stress (ksi)	Crack Length 2a (in)	Fail Stress (ksi)	Crack Length 2a (in)
3	36.2	.995	-	-
3	36.1	.999	-	-
3	36.1	.998	-	-
12	32.7	4.000	27.6	4.004
12	31.5	4.160	27.7	4.004
12	32.6	4.000	-	-
12	33.1	3.992	-	-
24	28.9	7.998	21.3	8.022
24	30.1	8.000	22.1	7.999
40	35.2	8.004	24.1	7.999
40	-	-	24.1	8.000
40	26.7	13.334	17.6	13.333
40	26.5	13.333	-	-

Table 4. Failure Stress for the M(T) TL Fracture Tests (B=0.063)

	M(T) TL constrained		M(T) TL unconstrained	
Width (inch)	Fail Stress (ksi)	Crack Length 2a (in)	Fail Stress (ksi)	Crack Length 2a (in)
3	33.2	.984	-	-
3	33.4	1.001	-	-
12	30.0	4.001	26.0	3.992
12	30.3	4.009	25.8	4.002
24	27.2	8.002	20.9	8.001
24	27.4	8.000	21.0	8.002

Table 5. Load and Crack Extension Measurements for 2 inch Wide C(T) LT Tests.

W=2in., a = 0.800		W=2in., a = 0.800		W=2in., a = 0.800	
Load (lbs)	Δa (inch)	Load (lbs)	Δa (inch)	Load (lbs)	Δa (inch)
583	0.005	557	0.012	650	0.010
652	0.025	651	0.028	684	0.033
690	0.049	696	0.06	702	0.053
704	0.099	709	0.106	716	0.073
705	0.148	705	0.156	718	0.101
676	0.196	678	0.198	712	0.134
626	0.243	636	0.234	685	0.191
568	0.307	593	0.265	654	0.221
494	0.354	523	0.307	614	0.259
426	0.408	500	0.348	556	0.302
		449	0.396	502	0.350
				458	0.399
				395	0.430

Table 6. Load and Crack Extension Measurements for 4 inch Wide C(T) LT Tests.

W=4in., a = 1.600 (a)		W=4in., a = 1.600		W=4in., a = 1.600	
Load (lbs)	Δa (inch)	Load (lbs)	Δa (inch)	Load (lbs)	Δa (inch)
697	0.003	802	0.003	704	0.004
801	0.006	897	0.014	799	0.007
897	0.009	995	0.019	899	0.009
996	0.019	1097	0.036	999	0.026
1100	0.041	1201	0.071	1102	0.060
1196	0.079	1231	0.111	1201	0.108
1242	0.112	1258	0.148	1240	0.142
1291	0.147	1268	0.189	1259	0.193
1306	0.184	1275	0.228	1261	0.232
1314	0.220	1260	0.270	1251	0.265
1313	0.250	1259	0.311	1238	0.319
1309	0.280	1225	0.359	1202	0.353
1291	0.309	1183	0.395	1173	0.409
1273	0.340	1150	0.443	1143	0.464
1247	0.380	1114	0.486	1084	0.500
1214	0.425	1067	0.543	1056	0.545
1167	0.485	1026	0.601	1019	0.591
1080	0.532	961	0.661	963	0.632
		908	0.707	926	0.687
		860	0.755	869	0.731
		818	0.806	828	0.777
		763	0.869	786	0.811
		714	0.925	751	0.878
		659	0.978	685	0.922
		605	1.039	650	0.988
				592	1.014

(a) surfaces developed V shear fracture

Table 7. Load and Crack Extension Measurements for 6 inch Wide C(T) LT Tests.

W=6in., a = 2.400 (a)		W=6in., a = 2.400		W=6in., a = 2.400	
Load (lbs)	Δa (inch)	Load (lbs)	Δa (inch)	Load (lbs)	Δa (inch)
1073	0.016	1132	0.026	1001	0.008
1232	0.025	1389	0.068	1109	0.015
1492	0.029	1514	0.102	1198	0.024
1594	0.094	1602	0.142	1299	0.031
1693	0.128	1666	0.179	1399	0.056
1765	0.173	1694	0.222	1500	0.076
1826	0.224	1719	0.265	1601	0.123
1843	0.307	1734	0.317	1670	0.171
1803	0.315	1737	0.379	1704	0.220
1778	0.43	1722	0.439	1725	0.256
1750	0.497	1699	0.512	1732	0.303
1684	0.572	1655	0.587	1734	0.357
1642	0.648	1602	0.667	1735	0.406
1567	0.743	1552	0.745	1710	0.449
1494	0.826	1494	0.843	1691	0.491
1492	0.884	1327	0.934	1683	0.540
1372	0.964	1247	1.025	1618	0.601
1293	1.043	1182	1.096	1596	0.663
1227	1.119	1074	1.216	1553	0.715
1158	1.197	1013	1.279	1508	0.760
1090	1.284	932	1.320	1468	0.816
1012	1.368	866	1.405	1424	0.884
937	1.435	792	1.557	1354	0.973
868	1.514	729	1.634	1263	1.042
820	1.598	680	1.720	1206	1.112
756	1.656	618	1.802	1145	1.182
698	1.759	556	1.875	1079	1.248
				1030	1.309
				972	1.369
				919	1.464
				850	1.551

(a) surfaces developed V shear fracture

Table 8. Load and Crack Extension Measurements for 6 inch Wide C(T) LT Tests.

W=6in., a = 2.400		W=6in., a = 2.400	
Load (lbs)	Δa (inch)	Load (lbs)	Δa (inch)
900	0.003	608	0.001
950	0.005	704	0.003
1001	0.005	804	0.005
1051	0.010	902	0.007
1102	0.012	1004	0.014
1154	0.017	1110	0.014
1200	0.021	1201	0.025
1252	0.028	1296	0.036
1299	0.038	1400	0.067
1349	0.044	1497	0.094
1401	0.055	1597	0.126
1454	0.072	1650	0.171
1500	0.090	1710	0.229
1551	0.103	1729	0.301
1602	0.125	1722	0.352
1653	0.156	1697	0.418
1686	0.201	1677	0.460
1726	0.242	1628	0.561
1742	0.288	1574	0.647
1742	0.340	1512	0.712
1749	0.381	1450	0.774
1746	0.439	1380	0.850
1722	0.509	1325	0.920
1700	0.562	1280	0.967
1648	0.617		
1612	0.681		
1552	0.768		
1478	0.834		
1442	0.899		
1357	0.992		

Table 9. Load and Crack Extension Measurements for 2 inch Wide C(T) TL Tests.

W=2in., a = 0.701		W=2in., a = 0.800		W=2in., a = 0.800	
Load (lbs)	Δa (inch)	Load (lbs)	Δa (inch)	Load (lbs)	Δa (inch)
602	0.011	550	0.003	556	0.013
658	0.017	650	0.019	601	0.016
706	0.026	672	0.070	652	0.040
754	0.051	692	0.107	665	0.094
785	0.094	683	0.152	666	0.132
773	0.144	642	0.189	652	0.177
741	0.186	606	0.223	615	0.224
720	0.243	570	0.270	560	0.274
656	0.305	523	0.321	508	0.324
607	0.365	461	0.353	448	0.373
534	0.426	424	0.398	417	0.424
457	0.478	398	0.420		

Table 10. Load and Crack Extension Measurements for 4 inch Wide C(T) TL Tests.

W=4in., a = 1.600		W=4in., a = 1.600		W=4in., a = 1.600	
Load (lbs)	Δa (inch)	Load (lbs)	Δa (inch)	Load (lbs)	Δa (inch)
612	0.006	699	0.001	701	0.006
700	0.006	797	0.003	799	0.012
799	0.009	898	0.013	877	0.019
897	0.019	1003	0.048	927	0.028
999	0.044	1103	0.107	985	0.042
1103	0.101	1149	0.151	1018	0.064
1151	0.159	1174	0.193	1049	0.076
1167	0.223	1188	0.235	1077	0.088
1168	0.252	1180	0.278	1100	0.102
1152	0.295	1158	0.335	1117	0.115
1131	0.336	1132	0.394	1128	0.137
1090	0.424	1081	0.431	1146	0.156
1040	0.487	1052	0.48	1158	0.179
980	0.529	1015	0.55	1164	0.202
935	0.572	964	0.591	1169	0.225
886	0.634	917	0.639	1162	0.258
826	0.697	864	0.686	1158	0.281
765	0.772	834	0.727	1149	0.312
		801	0.777	1136	0.344
		752	0.841	1105	0.396
		680	0.898	1084	0.443
		644	0.941	1050	0.468
		606	1.002	1018	0.541
				997	0.583
				932	0.626
				893	0.680
				842	0.736
				800	0.786
				750	0.834
				704	0.880
				669	0.938
				615	1.000
				842	0.736
				800	0.786
				750	0.834
				704	0.880
				669	0.938
				615	1.000

Table 11. Load and Crack Extension Measurements for 6 inch Wide C(T) TL Tests.

W=6in., a = 2.400		W=6in., a = 2.400		W=6in., a = 2.400	
Load (lbs)	Δa (inch)	Load (lbs)	Δa (inch)	Load (lbs)	Δa (inch)
945	0.011	801	0.002	902	0.004
1123	0.025	903	0.006	1003	0.007
1236	0.049	1001	0.010	1102	0.015
1395	0.098	1100	0.019	1200	0.027
1495	0.150	1195	0.036	1300	0.055
1547	0.209	1297	0.061	1397	0.100
1584	0.269	1399	0.099	1489	0.149
1600	0.325	1496	0.140	1569	0.198
1600	0.372	1548	0.183	1600	0.243
1587	0.441	1598	0.236	1613	0.287
1570	0.518	1625	0.400	1626	0.336
1550	0.572	1626	0.438	1623	0.401
1512	0.658	1615	0.467	1601	0.449
1445	0.722	1576	0.552	1573	0.513
1399	0.797	1547	0.604	1541	0.574
1336	0.875	1492	0.682	1509	0.644
1278	0.949	1466	0.731	1470	0.698
1221	1.015	1418	0.794	1420	0.748
1156	1.072	1351	0.856	1388	0.814
1115	1.149	1299	0.943	1332	0.866
1060	1.226	1246	1.010	1291	0.926
1000	1.295	1195	1.109	1243	0.995
934	1.35	1115	1.175	1189	1.114
893	1.421	1066	1.239		
836	1.491	1018	1.296		
770	1.550	975	1.382		
729	1.629	898	1.473		
681	1.692	829	1.546		
650	1.774	770	1.606		
		699	1.745		
		629	1.797		
		593	1.858		
		555	1.922		
		515	1.994		

Table 12. Load and Crack Extension Measurements for 3 inch Wide M(T) LT Tests.

W=3in., 2a = .995		W=3in., 2a = .999		W=3in., 2a = .998	
Load (lbs)	2a (inch)	Load (lbs)	2a (inch)	Load (lbs)	2a (inch)
2740	0.995	2520	0.999	4970	0.998
2950	0.997	3010	0.999	5500	0.999
3150	0.999	3520	0.999	5980	1.002
3350	0.999	4000	1.002	6490	1.023
3550	1.000	4510	1.002	6720	1.059
3770	1.003	5020	1.002	6810	1.098
3960	1.005	5510	1.002	6820	1.110
4150	1.005	6010	1.005	6790	1.136
4341	1.005	6480	1.029	6730	1.177
4550	1.005	6750	1.105	6690	1.219
4760	1.006	6820	1.152	6630	1.262
4940	1.006	6760	1.183	6500	1.310
5340	1.018	6710	1.247	6340	1.378
5730	1.019	6230	1.405	6170	1.453
6130	1.022	6060	1.501	5910	1.517
6500	1.038	5740	1.571	5720	1.672
6790	1.085	5530	1.663	5110	1.760
6850	1.105	5150	1.709	4850	1.920
6770	1.165	5110	1.849	4240	1.984
6710	1.193	4480	1.903	4120	2.141
6680	1.227	4340	2.018		
6480	1.339				
6260	1.419				
6040	1.524				
5660	1.607				
5390	1.807				

Table 13. Load and Crack Extension Measurements for 12 inch Wide M(T) LT Tests.

W=12in., constrained 2a = 4.000			W=12in., constrained 2a = 4.160		
Load (kips)	Δa (inch)	Δa (inch)	Load (kips)	Δa (inch)	Δa (inch)
11.04	0.007	0.005	11.00	0.003	0.005
12.02	0.009	0.008	12.00	0.006	0.009
13.01	0.012	0.010	13.00	0.009	0.013
14.03	0.014	0.013	14.02	0.012	0.015
15.01	0.020	0.016	15.02	0.016	0.023
16.01	0.029	0.023	16.01	0.021	0.029
17.03	0.033	0.030	17.02	0.042	0.040
18.03	0.055	0.049	18.02	0.055	0.054
19.01	0.070	0.059	19.02	0.071	0.071
20.01	0.089	0.080	20.03	0.087	0.094
21.03	0.111	0.104	21.02	0.116	0.118
22.01	0.152	0.124	22.02	0.152	0.151
23.02	0.170	0.156	22.51	0.179	0.175
23.93	0.222	0.212	23.02	0.209	0.207
24.44	0.275	0.271	23.48	0.266	0.257
24.64	0.333	0.325	23.69	0.310	0.304
24.74	0.419	0.398	23.80	0.357	0.359
24.61	0.475	0.460	23.81	0.405	0.396
24.37	0.561	0.532	23.80	0.453	0.455
24.01	0.65	0.594	23.61	0.500	0.506
23.62	0.735	0.701	23.43	0.576	0.601
23.13	0.803	0.755	23.07	0.640	0.660
22.77	0.925	0.887	22.73	0.683	0.706
21.97	1.020	0.955	22.54	0.758	0.762
21.59	1.173	1.114	22.15	0.865	0.903
20.44	1.296	1.190	21.42	0.950	1.027
19.94	1.343	1.305	20.78	1.623	1.142
19.38	1.631	1.395	20.13	1.192	1.202
18.15	1.686	1.740	19.44	1.285	1.343
16.65	1.993	1.828	18.70	1.496	1.450
			17.63	1.559	1.606
			16.90	1.766	1.657

Table 14. Load and Crack Extension Measurements for 12 inch Wide M(T) LT Tests.

W=12in., constrained 2a = 4.000			W=12in., constrained 2a = 3.992		
Load (kips)	Δa (inch)	Δa (inch)	Load (kips)	Δa (inch)	Δa (inch)
10.03	0.007	0.005	10.03	0.006	0.004
11.01	0.008	0.009	11.03	0.006	0.007
12.01	0.009	0.010	12.02	0.011	0.012
13.01	0.01	0.013	13.02	0.015	0.014
14.02	0.014	0.016	14.02	0.015	0.018
15.02	0.018	0.019	15.03	0.020	0.023
16.02	0.026	0.030	16.02	0.025	0.025
17.03	0.030	0.039	17.02	0.026	0.034
18.02	0.039	0.053	18.02	0.029	0.035
19.09	0.069	0.067	18.02	0.044	0.038
20.02	0.080	0.085	19.02	0.057	0.049
21.02	0.101	0.107	20.02	0.084	0.065
22.01	0.126	0.128	21.02	0.101	0.092
23.01	0.164	0.162	22.02	0.128	0.108
23.95	0.217	0.226	23.03	0.166	0.146
24.36	0.275	0.284	24.02	0.217	0.190
24.58	0.319	0.331	24.64	0.282	0.242
24.68	0.357	0.382	24.87	0.341	0.290
24.57	0.423	0.448	25.02	0.397	0.343
24.51	0.492	0.535	24.90	0.450	0.376
24.07	0.573	0.606	24.79	0.526	0.433
23.76	0.647	0.683	24.49	0.609	0.528
23.29	0.744	0.790	24.00	0.670	0.613
22.68	0.857	0.917	23.57	0.761	0.739
22.15	0.900	0.986	23.02	0.844	0.808
21.77	0.930	1.051	22.52	1.013	0.936
21.50	1.047	1.100	21.62	1.158	1.061
20.93	1.086	1.165	20.75	1.212	1.169
20.65	1.190	1.226	20.22	1.321	1.309
20.09	1.240	1.330	19.32	1.452	1.488
19.55	1.324	1.447	18.38	1.508	1.660
18.92	1.515	1.546	17.60	1.542	1.714
17.70	1.599	1.890	17.60	1.854	1.795
16.40	2.143	1.671	15.96	1.895	2.399

Table 15. Load and Crack Extension Measurements for 12 inch Wide M(T) LT Tests.

W=12in., unconstrained 2a = 4.004			W=12in., unconstrained 2a = 4.004		
Load (kips)	Δa (inch)	Δa (inch)	Load (kips)	Δa (inch)	Δa (inch)
12.00	0.009	0.002	10.02	0.003	0.001
13.01	0.012	0.005	11.02	0.008	0.008
14.00	0.018	0.010	12.02	0.017	0.014
15.03	0.025	0.022	13.01	0.023	0.022
16.01	0.043	0.038	14.03	0.028	0.026
17.02	0.070	0.067	15.02	0.039	0.034
18.01	0.083	0.083	16.03	0.052	0.063
19.01	0.121	0.111	17.01	0.080	0.072
19.51	0.132	0.134	18.01	0.100	0.093
20.00	0.181	0.164	19.01	0.135	0.121
20.51	0.237	0.215	20.03	0.197	0.186
20.68	0.270	0.257	20.57	0.252	0.241
20.80	0.316	0.294	20.76	0.312	0.301
20.86	0.360	0.343	20.89	0.401	0.362
20.86	0.401	0.406	20.93	0.460	0.423
20.74	0.467	0.467	20.77	0.528	0.528
20.57	0.555	0.542	20.62	0.608	0.561
20.25	0.588	0.577	20.32	0.602	0.602
20.18	0.647	0.646	20.19	0.700	0.621
19.85	0.759	0.783	20.10	0.756	0.721
19.23	0.801	0.831	19.53	0.883	0.822
19.04	0.852	0.869	19.04	1.022	0.964
18.76	0.942	0.929	18.22	1.225	1.145
18.38	1.167	1.129	17.14	1.359	1.251
17.10	1.206	1.169	16.44	1.883	1.454
16.97	1.486	1.400	14.87	1.923	1.803
15.41	1.947	1.589	13.18	2.113	2.113
15.42	1.968	1.689	10.90	2.437	2.437
13.16	2.380	1.893			

Table 16. Load and Crack Extension Measurements for 24 inch Wide M(T) LT Tests.

W=24in., constrained 2a =7.998			W=24in., constrained 2a = 8.000		
Load (kips)	Δa (inch)	Δa (inch)	Load (kips)	Δa (inch)	Δa (inch)
18.00	0.008	0.008	20.10	0.015	0.011
19.07	0.011	0.012	21.76	0.022	0.010
20.04	0.018	0.021	23.00	0.027	0.021
21.06	0.020	0.024	24.02	0.029	0.029
22.04	0.027	0.029	25.02	0.034	0.031
23.04	0.032	0.035	26.08	0.044	0.038
24.04	0.040	0.042	27.04	0.050	0.040
25.00	0.045	0.049	28.50	0.070	0.064
26.00	0.058	0.062	29.02	0.073	0.066
22.04	0.068	0.071	30.00	0.075	0.079
28.04	0.078	0.079	31.00	0.091	0.079
29.02	0.085	0.090	32.00	0.096	0.092
30.03	0.101	0.103	33.00	0.113	0.111
31.00	0.111	0.112	34.00	0.131	0.118
32.02	0.136	0.135	35.04	0.145	0.133
33.02	0.153	0.151	36.00	0.171	0.154
34.00	0.201	0.176	37.04	0.185	0.178
35.04	0.226	0.190	38.02	0.226	0.197
36.02	0.260	0.217	39.40	0.279	0.209
37.04	0.289	0.247	40.02	0.290	0.282
38.02	0.334	0.280	40.76	0.327	0.305
38.00	0.395	0.315	42.00	0.372	0.355
39.98	0.449	0.370	42.78	0.428	0.392
40.76	0.506	0.460	43.26	0.471	0.443
41.28	0.551	0.458	43.72	0.522	0.484
41.80	0.611	0.531	44.08	0.563	0.555
42.32	0.673	0.602	44.56	0.630	0.605
42.68	0.751	0.656	44.96	0.711	0.658
43.10	0.809	0.726	45.14	0.785	0.753
43.26	0.869	0.778	45.32	0.880	0.827
43.35	0.869	0.835	45.46	0.983	0.928
43.56	0.922	0.934	45.36	1.278	1.035
43.72	1.081	1.036	44.74	1.326	1.309
43.70	1.779	1.200	44.52	1.522	1.409
			43.60	1.807	1.842

Table 17. Load and Crack Extension Measurements for 24 inch Wide M(T) LT Tests.

W=24in., unconstrained 2a = 8.022			W=24 in., unconstrained 2a = 7.999		
Load (kips)	Δa (inch)	Δa (inch)	Load (kips)	Δa (inch)	Δa (inch)
15.02	0.003	0.008	15.00	0.006	0.007
16.00	0.005	0.009	16.00	0.009	0.009
17.00	0.008	0.012	17.02	0.012	0.013
18.02	0.016	0.020	18.04	0.018	0.018
19.02	0.018	0.023	19.00	0.023	0.020
20.00	0.025	0.035	20.04	0.003	0.027
21.00	0.031	0.044	21.02	0.037	0.034
22.02	0.040	0.054	22.02	0.047	0.045
23.02	0.054	0.069	23.00	0.057	0.051
24.00	0.070	0.083	24.04	0.065	0.067
25.04	0.086	0.098	25.02	0.081	0.080
26.02	0.107	0.123	26.04	0.096	0.093
27.00	0.133	0.147	27.08	0.121	0.113
28.00	0.156	0.176	27.98	0.144	0.138
29.00	0.198	0.216	29.00	0.170	0.165
29.52	0.216	0.242	30.04	0.205	0.218
30.00	0.251	0.279	30.62	0.234	0.240
30.52	0.293	0.316	31.48	0.281	0.299
31.00	0.340	0.376	32.10	0.345	0.344
31.36	0.394	0.427	32.36	0.379	0.383
31.48	0.431	0.500	32.58	0.438	0.447
31.70	0.483	0.567	32.80	0.477	0.491
32.00	0.558	0.649	33.02	0.549	0.549
32.06	0.581	0.693	33.20	0.584	0.589
32.08	0.664	0.770	33.30	0.659	0.660
32.22	0.812	0.924	33.28	0.724	0.721
31.90	0.830	0.967	33.32	0.777	0.776
31.92	0.884	1.005	33.20	0.824	0.835
31.94	1.017	1.155	33.34	0.871	0.880
31.50	1.108	1.245	33.18	1.053	1.132
31.24	1.148	1.316	32.76	1.400	1.397
31.22	1.317	1.528	31.92	1.767	1.730
			30.64	2.087	2.014
			29.40	2.112	2.106
			29.10	2.458	2.415
			27.72	2.542	2.518
			27.56	2.918	2.812
			25.90	2.972	2.853
			25.90	2.972	2.853

Table 18. Load and Crack Extension Measurements for 40 inch Wide M(T) LT Tests.

W=40in., constrained 2a=13.334			W=40in., constrained 2a = 13.334		
Load (kips)	Δa (inch)	Δa (inch)	Load (kips)	Δa (inch)	Δa (inch)
15.00	0.004	0.004	15.64	0.004	0.003
15.90	0.007	0.009	19.66	0.005	0.006
16.98	0.010	0.011	23.68	0.009	0.006
18.02	0.018	0.014	27.68	0.019	0.017
19.02	0.017	0.015	31.70	0.043	0.040
19.98	0.019	0.017	35.68	0.072	0.067
20.98	0.017	0.025	37.68	0.078	0.092
22.00	0.027	0.026	39.68	0.094	0.103
22.94	0.030	0.023	41.70	0.115	0.123
23.98	0.011	0.013	43.70	0.130	0.149
25.60	0.013	0.014	45.70	0.156	0.180
26.02	0.018	0.016	47.70	0.200	0.212
27.00	0.021	0.023	49.64	0.227	0.254
28.00	0.025	0.023	51.64	0.261	0.303
29.04	0.025	0.028	53.68	0.316	0.345
30.00	0.032	0.037	54.78	0.335	0.387
31.04	0.037	0.042	56.18	0.387	0.438
32.00	0.040	0.047	57.32	0.429	0.483
33.60	0.057	0.062	58.80	0.494	0.547
33.98	0.058	0.064	59.86	0.543	0.608
35.00	0.062	0.067	60.52	0.599	0.664
36.02	0.067	0.079	61.56	0.664	0.735
37.02	0.074	0.088	62.46	0.736	0.835
38.02	0.080	0.093	63.12	0.785	0.897
39.02	0.086	0.105	64.22	0.912	1.029
40.02	0.105	0.115	64.82	0.987	1.094
41.04	0.124	0.128	65.26	1.047	1.229
44.02	0.141	0.158	65.66	1.124	1.288
47.02	0.196	0.219	65.98	1.197	1.408
47.02	0.222	0.262	66.42	1.297	1.490
47.80	0.272	0.317	66.82	1.397	1.624
50.04	0.333	0.385	66.88	1.461	1.706
52.04	0.478	0.562	67.12	1.571	1.812
54.06	0.564	0.673	67.32	1.698	1.912
58.04	0.732	0.841	67.38	1.774	2.053
60.04	0.935	1.059	67.32	2.174	2.414
62.02	1.253	1.449	67.02	2.286	2.508
64.04	1.581	1.778	66.84	2.323	2.571
66.04	1.923	2.127	66.74	2.757	3.006
66.48	2.399	2.575	65.76	2.917	3.270
66.86	2.586	2.783			
66.68	2.953	3.089			
66.20	3.060	3.324			
65.56	3.514	3.987			
64.77	3.680	4.372			

Table 19. Load and Crack Extension Measurements for 40 inch Wide M(T) LT Tests.

W=40in., unconstrained 2a=13.333			W=40in., constrained 2a = 8.004		
Load (kips)	Δa (inch)	Δa (inch)	Load (kips)	Δa (inch)	Δa (inch)
23.02	0.012	0.007	29.98	0.001	0.001
24.00	0.020	0.011	35.00	0.004	0.006
25.02	0.025	0.019	40.02	0.012	0.008
26.02	0.027	0.021	44.98	0.002	0.030
22.10	0.035	0.033	50.02	0.047	0.056
28.02	0.038	0.053	55.00	0.084	0.084
29.18	0.051	0.035	60.00	0.122	0.123
30.02	0.061	0.062	65.00	0.176	0.173
31.02	0.074	0.073	70.00	0.249	0.247
32.00	0.086	0.091	75.00	0.366	0.348
33.00	0.095	0.106	80.02	0.530	0.527
34.00	0.109	0.130	82.50	0.654	0.659
35.00	0.140	0.152	85.00	0.837	0.832
36.00	0.165	0.175	86.72	1.259	1.024
37.00	0.200	0.204	87.72	1.259	1.267
38.00	0.226	0.240	88.32	1.439	1.377
39.00	0.272	0.285	88.72	1.648	1.600
39.64	0.313	0.350	88.70	-	1.793
40.02	0.333	0.349	88.78	-	1.199
40.70	0.400	0.393	88.30	-	2.297
41.20	0.446	0.446	87.62	-	2.569
41.66	0.491	0.486	86.72	-	2.855
41.98	0.524	0.524	85.52	-	3.040
42.38	0.588	0.574	81.72	-	3.318
42.80	0.641	0.639			
43.12	0.703	0.690			
43.32	0.723	0.744			
43.64	0.763	0.805			
43.84	0.831	0.869			
44.10	0.887	0.927			
44.28	0.934	1.002			
44.44	1.024	1.117			
44.42	1.304	1.292			
44.42	1.436	1.448			
44.12	1.651	1.752			
44.06	1.908	1.948			
43.20	3.158	2.602			

Table 20. Load and Crack Extension Measurements for 40 inch Wide M(T) LT Tests.

W=40in., unconstrained 2a=8.000			W=40in., unconstrained 2a = 7.999		
Load (kips)	Δa (inch)	Δa (inch)	Load (kips)	Δa (inch)	Δa (inch)
22.96	0.002	0.003	32.04	0.005	-
24.96	0.003	0.007	34.02	0.012	-
27.74	0.006	0.008	36.04	0.016	-
29.52	0.012	0.014	45.04	0.081	-
31.94	0.017	0.024	50.04	0.143	-
33.92	0.023	0.029	55.04	0.263	-
35.94	0.029	0.034	59.94	0.603	-
37.94	0.044	0.046	60.22	0.634	-
39.94	0.052	0.061	60.22	0.703	-
41.94	0.066	0.081	60.42	0.858	-
43.96	0.092	0.100	60.8	1.386	-
45.98	0.114	0.118	60.46	1.749	-
47.96	0.138	0.143	59.72	2.300	-
49.96	0.166	0.181	58.06	3.084	-
51.20	0.197	0.221			
52.96	0.236	0.254			
53.72	0.255	0.286			
54.24	0.286	0.324			
55.36	0.339	0.378			
56.38	0.385	0.423			
56.92	0.421	0.464			
57.42	0.462	0.518			
58.04	0.512	0.580			
58.56	0.557	0.651			
59.78	0.754	0.836			
60.02	0.809	0.895			
60.48	0.862	0.978			
60.20	0.894	1.034			
60.36	0.939	1.063			
60.68	1.059	1.223			
60.46	1.097	1.256			
60.48	1.118	1.304			
60.52	1.214	1.418			
60.38	1.374	1.576			
60.08	1.383	1.657			
57.04	2.498	3.198			
56.10	2.522	3.227			
55.36	2.639	3.463			
55.26	2.990	3.805			
53.88	3.020	3.911			
53.90	3.351	4.490			
52.14	3.710	5.309			

Table 21. Load and Crack Extension Measurements for 3 inch Wide M(T) TL Tests.

W=3in., constrained 2a = .984		W=3in., constrained 2a = 1.001	
Load (lbs)	2a (inch)	Load (lbs)	2a (inch)
518	0.984	3990	1.001
1510	0.986	4490	1.003
2005	0.989	5000	1.007
2510	0.989	5490	1.016
3607	0.989	6000	1.044
6207	1.105	6230	1.144
6314	1.237	6270	1.195
5986	1.299	6130	1.262
5802	1.416	6060	1.341
4953	1.604	5910	1.410
4847	1.695	5740	1.460
4470	1.831	5550	1.564
		5240	1.624
		5080	1.698
		4770	1.799
		4490	1.871
		4250	2.019
		3710	2.140

Table 22. Load and Crack Extension Measurements for 12 inch Wide M(T) TL Tests.

W=12in., constrained 2a = 4.001			W=12in., constrained 2a = 4.009		
Load (kips)	Δa (inch)	Δa (inch)	Load (kips)	Δa (inch)	Δa (inch)
13.81	0.010	0.015	12.55	0.004	0.009
16.23	0.041	0.025	15.50	0.018	0.019
18.39	0.077	0.067	17.80	0.030	0.068
19.76	0.112	0.110	18.79	0.054	0.096
20.90	0.162	0.149	19.37	0.085	0.109
21.93	0.216	0.223	20.61	0.131	0.143
22.36	0.274	0.273	21.39	0.171	0.187
22.59	0.326	0.318	21.94	0.212	0.241
22.71	0.380	0.390	22.42	0.265	0.293
22.70	0.449	0.460	22.66	0.320	0.330
22.59	0.512	0.559	22.78	0.372	0.381
22.40	0.580	0.607	22.87	0.434	0.447
22.21	0.677	0.680	22.71	0.497	0.510
21.84	0.745	0.751	22.57	0.555	0.554
21.46	0.872	0.883	22.42	0.627	0.609
20.89	0.946	0.939	22.18	0.692	0.697
20.62	1.020	1.022	21.89	0.779	0.756
20.14	1.117	1.099	21.54	0.855	0.832
19.65	1.361	1.281	21.18	0.989	0.981
18.37	1.438	1.402	20.40	1.070	1.039
17.86	1.681	1.606	20.12	1.220	1.195
16.40	1.739	1.797	19.18	1.486	1.293
15.67	2.098	1.982	18.10	1.650	1.634
			16.42	1.760	2.025
			14.90	2.158	2.065

Table 23. Load and Crack Extension Measurements for 12 inch Wide M(T) TL Tests.

W=12in., unconstrained 2a = 3.992		W=12in., unconstrained 2a = 4.002	
Load (kips)	2a (inch)	Load (kips)	2a (inch)
12.01	3.999	12.03	4.01
13.01	4.012	14.02	4.028
14.00	4.018	16.02	4.073
15.01	4.031	17.01	4.125
16.01	4.070	18.01	4.229
17.01	4.140	18.30	4.280
17.53	4.185	18.77	4.338
18.02	4.244	19.01	4.409
18.53	4.302	19.23	4.492
19.02	4.386	19.36	4.568
19.51	4.531	19.44	4.657
19.64	4.698	19.48	4.748
19.64	4.853	19.43	4.832
19.54	5.193	19.43	4.956
19.03	5.595	18.75	5.233
18.05	6.105	18.86	5.373
16.83	6.846	18.54	5.492
14.72	7.597	18.30	5.713
		17.79	5.809
		17.51	6.330
		16.15	7.113
		13.95	7.624
		12.50	8.482

Table 24. Load and Crack Extension Measurements for 24 inch Wide M(T) TL Tests.

W=24in., constrained 2a = 8.000			W=24in., constrained 2a = 8.002		
Load (kips)	Δa (inch)	Δa (inch)	Load (kips)	Δa (inch)	Δa (inch)
14.06	0.000	0.001	19.04	0.003	0.011
15.00	0.002	0.002	21.02	0.004	0.018
16.00	0.005	0.004	22.02	0.012	0.023
17.00	0.005	0.004	23.02	0.020	0.026
18.00	0.006	0.006	24.02	0.035	0.038
19.02	0.006	0.006	25.04	0.038	0.053
20.02	0.010	0.008	26.00	0.042	0.065
21.00	0.018	0.018	27.08	0.053	0.069
22.00	0.027	0.022	28.04	0.094	0.112
23.02	0.032	0.031	29.50	0.155	0.174
24.02	0.039	0.041	32.06	0.160	0.194
25.02	0.054	0.051	33.00	0.189	0.217
26.06	0.068	0.061	34.02	0.244	0.246
27.96	0.082	0.081	35.00	0.270	0.286
28.00	0.084	0.083	36.06	0.314	0.337
29.00	0.100	0.103	37.00	0.375	0.401
30.02	0.113	0.115	38.02	0.445	0.493
31.00	0.138	0.134	38.90	0.510	0.545
32.04	0.158	0.153	39.62	0.576	0.611
33.06	0.171	0.187	39.94	0.647	0.706
34.02	0.204	0.214	40.34	0.703	0.757
35.00	0.226	0.237	40.72	0.703	0.871
36.06	0.264	0.275	40.90	0.827	0.983
37.00	0.306	0.313	41.06	0.937	1.066
38.02	0.382	0.385	41.16	1.007	1.153
38.90	0.458	0.457	41.02	1.153	1.287
39.52	0.523	0.525	41.08	1.251	1.375
39.92	0.579	0.577	40.72	1.398	1.584
40.54	0.682	0.649	40.58	1.484	1.729
40.90	0.787	0.773	40.00	1.737	2.019
41.28	0.902	0.897	39.64	1.846	2.150
41.48	1.002	1.027	38.46	2.147	2.294
41.26	1.129	1.115			
41.24	1.291	1.210			
40.86	1.365	1.378			
40.68	1.522	1.448			
40.34	1.697	1.643			
39.68	2.378	2.000			

Table 25. Load and Crack Extension Measurements for 24 inch Wide M(T) TL Tests.

W=24in., unconstrained 2a = 8.001			W=24in., unconstrained 2a = 8.002		
Load (kips)	Δa (inch)	Δa (inch)	Load (kips)	Δa (inch)	Δa (inch)
16.02	0.006	0.007	16.36	0.006	0.004
18.02	0.014	0.011	17.20	0.008	0.007
20.06	0.029	0.024	18.84	0.011	0.018
21.02	0.038	0.037	20.06	0.021	0.015
22.05	0.066	0.065	21.02	0.031	0.018
24.14	0.087	0.091	22.00	0.037	0.038
25.56	0.115	0.127	23.04	0.050	0.067
26.32	0.130	0.160	24.02	0.066	0.094
27.36	0.169	0.186	25.02	0.094	0.110
27.92	0.205	0.216	26.04	0.131	0.151
28.62	0.235	0.249	27.04	0.158	0.188
29.16	0.278	0.290	28.00	0.194	0.233
29.56	0.314	0.318	28.92	0.249	0.281
30.26	0.425	0.389	29.44	0.308	0.334
30.70	0.465	0.432	29.96	0.355	0.396
30.95	0.524	0.479	30.42	0.425	0.442
31.18	0.575	0.544	30.76	0.450	0.495
31.22	0.642	0.582	31.12	0.488	0.543
31.34	0.673	0.647	31.32	0.564	0.607
31.47	0.773	0.719	31.50	0.633	0.674
31.40	0.815	0.777	31.62	0.716	0.788
31.42	0.848	0.840	31.64	0.748	0.832
31.54	1.016	0.938	31.68	0.841	0.904
31.12	1.034	1.085	31.62	0.948	1.012
30.30	2.435	2.472	31.50	1.042	1.099
26.80	2.758	2.530	31.34	1.320	1.341
22.92	3.631	3.305	31.12	1.441	1.502
			30.62	1.598	1.699
			30.14	1.653	1.822
			29.74	1.848	2.046
			28.98	1.923	2.126
			28.66	2.219	2.553
			27.40	2.599	2.675
			26.46	2.627	3.259
			25.22	2.654	2.938

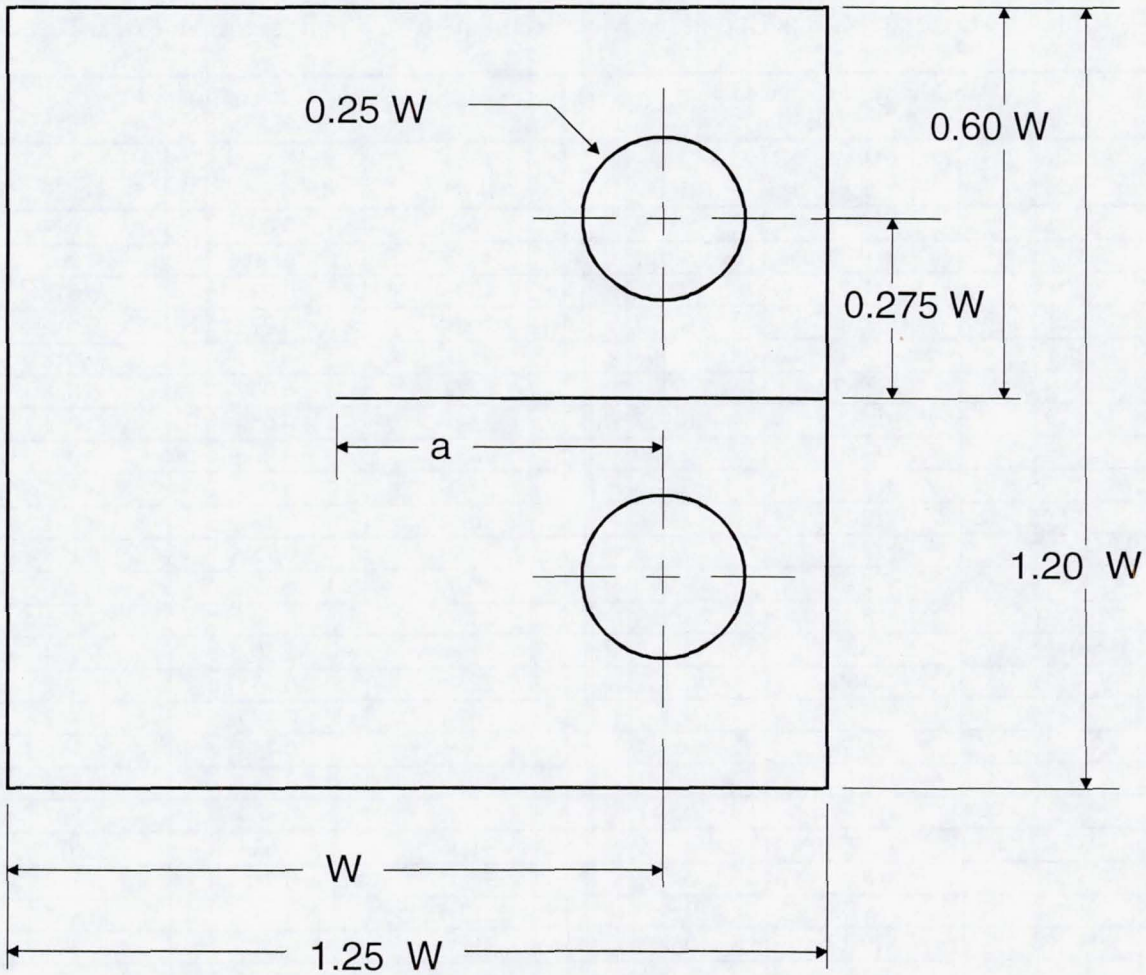
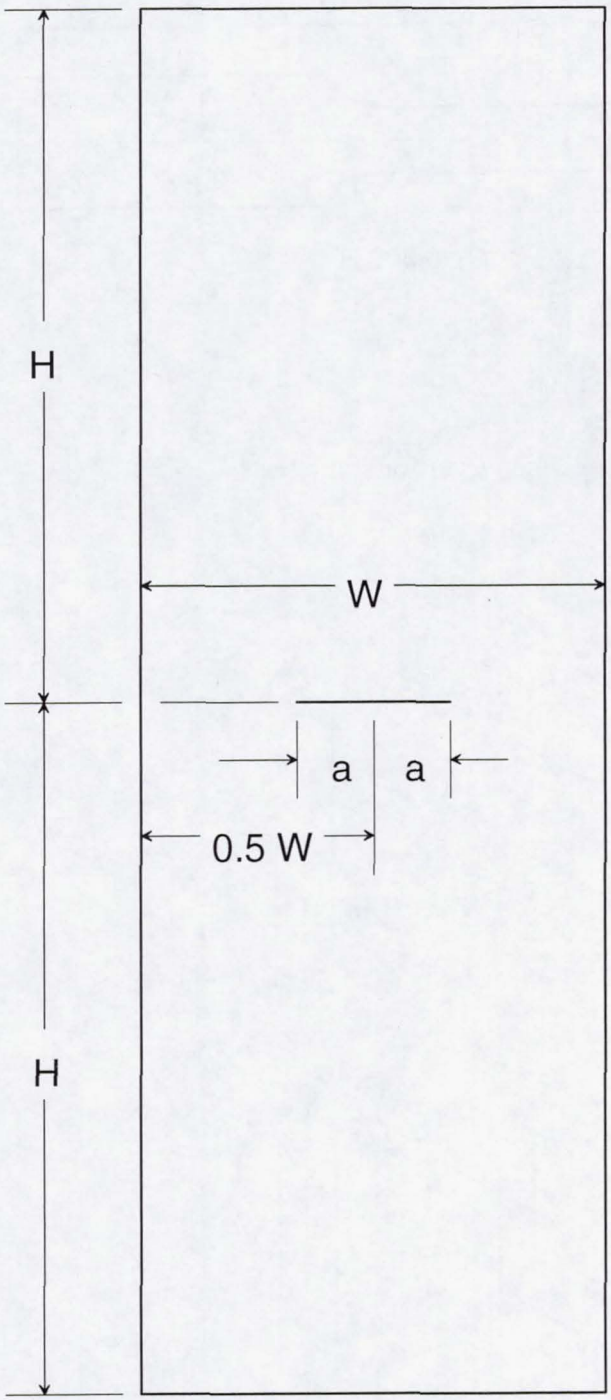


Figure 1. Schematic of a compact tension specimen (W = specimen width).



Specimen Width W, (in)	Specimen Height H, (in)
3.0	6.0
12.0	26.5
24.0 (TL)	38.5
24.0 (LT)	50.5
40.0	70.5

Figure 2. Schematic of a middle tension specimen (W = specimen width).

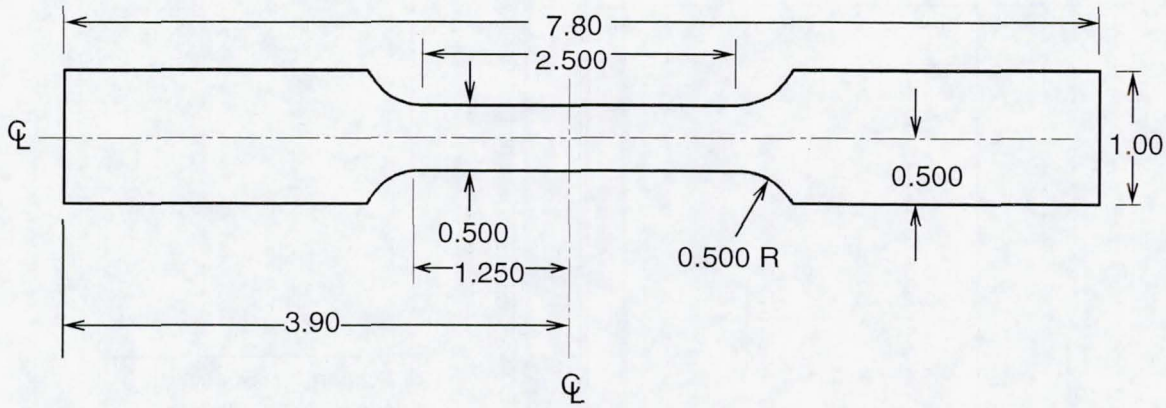


Figure 3. Tensile specimen used for static tests.

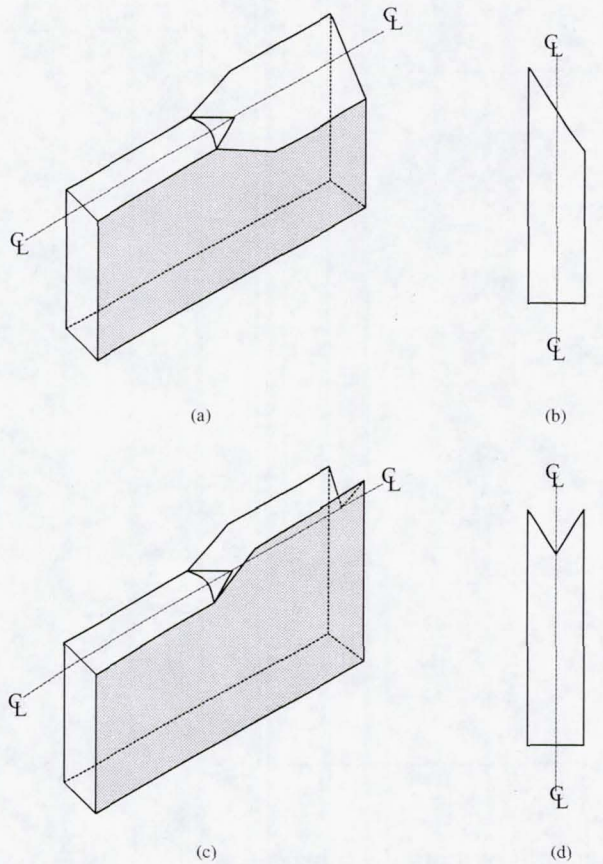


Figure 4. Schematic of slant-fracture (a, b) and V-fracture (c, d) behavior.

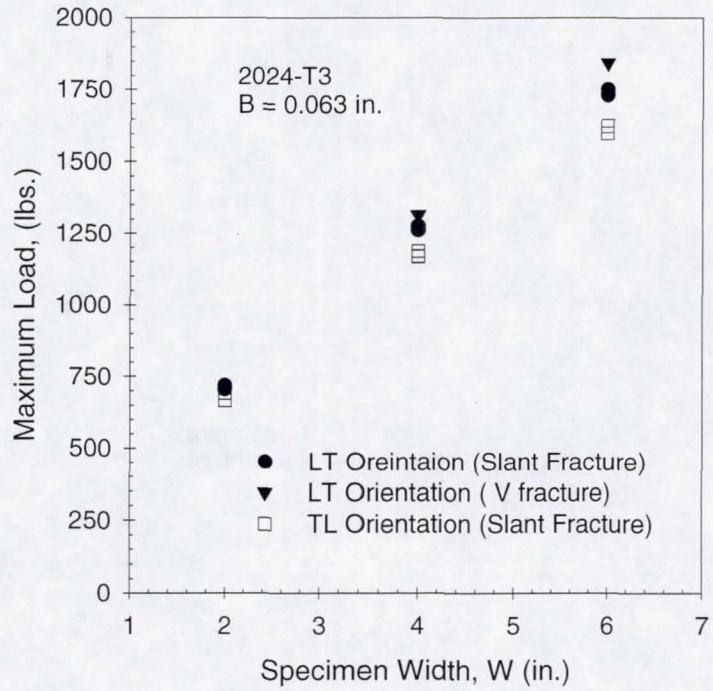


Figure 5. Failure loads for C(T) specimens of different widths.

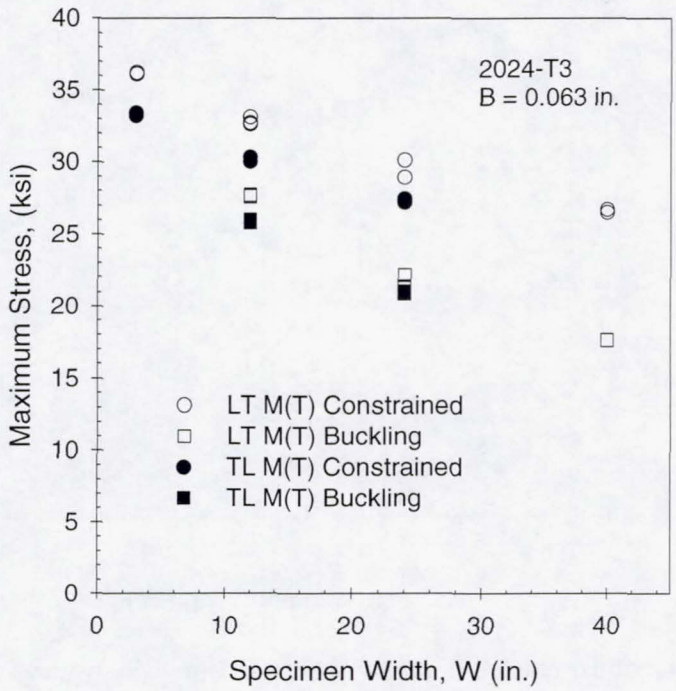


Figure 6. Failure stress results for M(T) specimens of different widths.

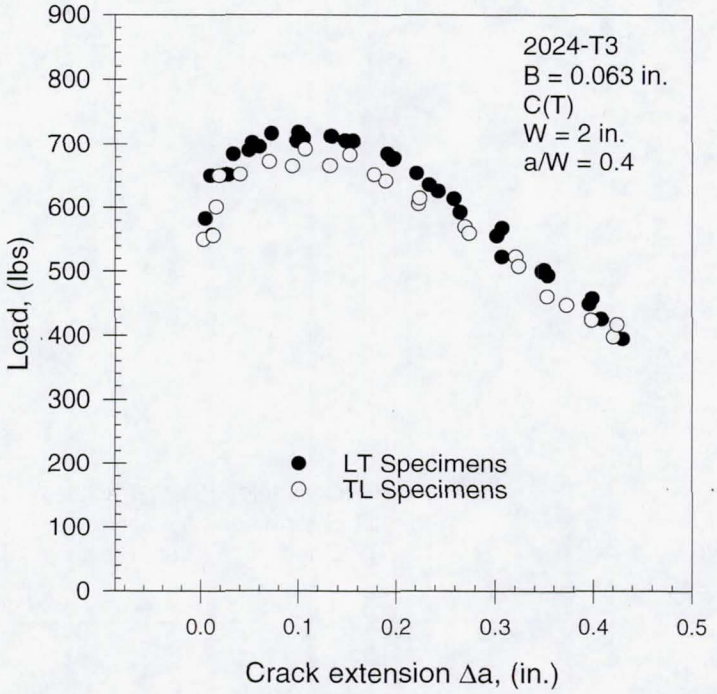


Figure 7. Load against crack extension results for the 2-inch-wide C(T) specimen.

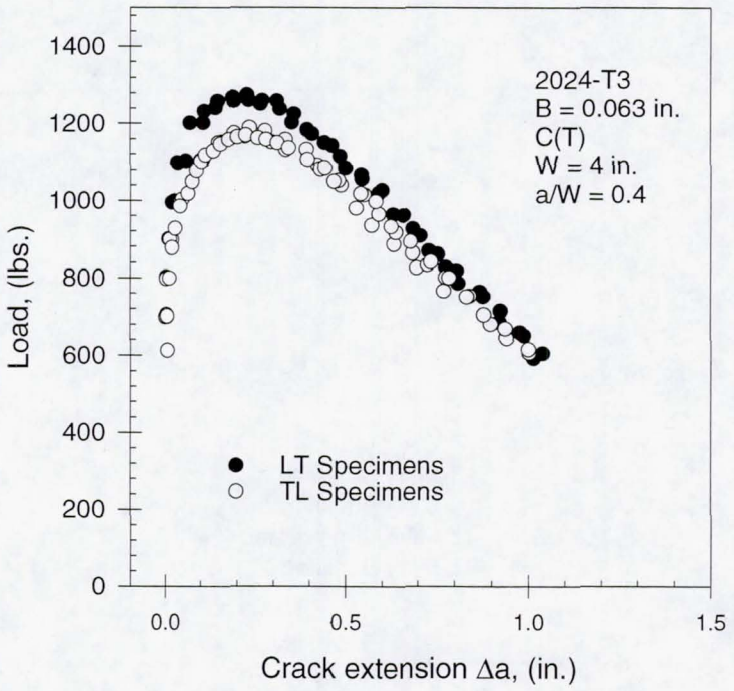


Figure 8. Load against crack extension results for the 4-inch-wide C(T) specimen.

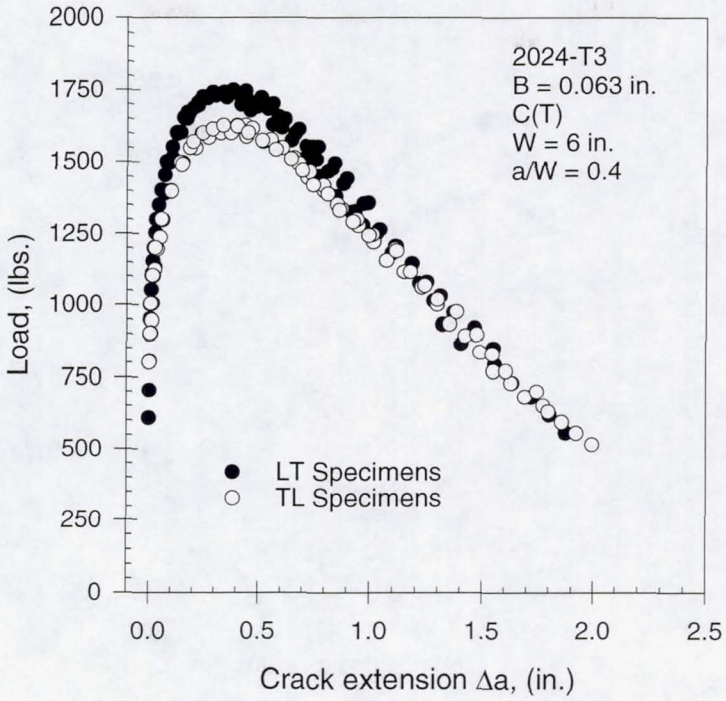


Figure 9. Load against crack extension results for the 6-inch-wide C(T) specimen.

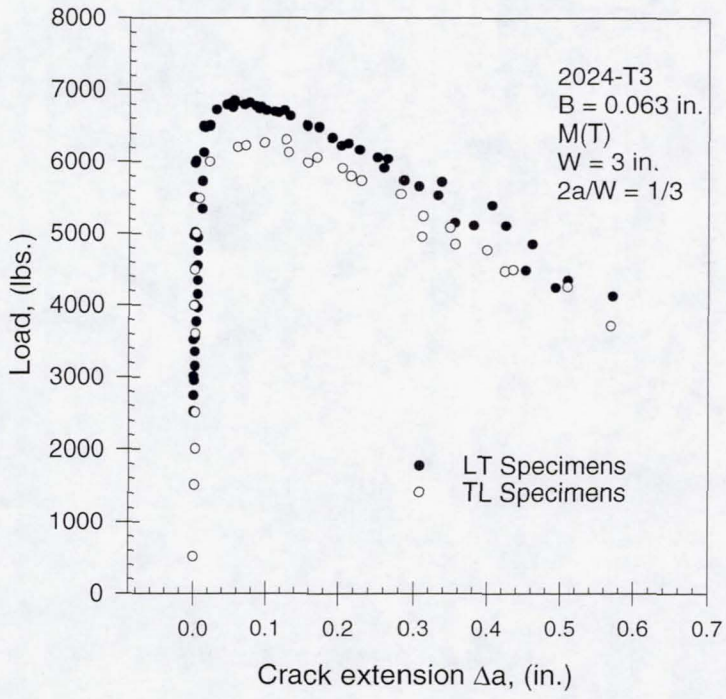


Figure 10. Load against crack extension results for the 3-inch-wide M(T) specimen.

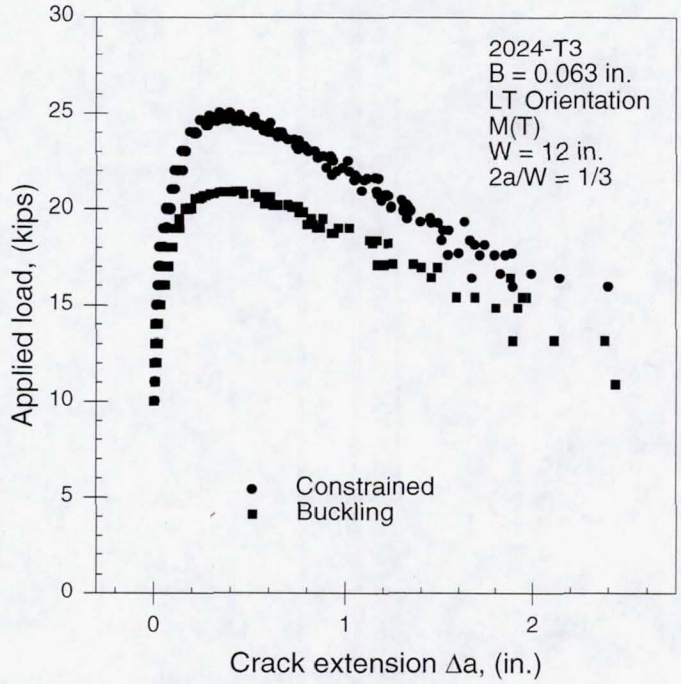


Figure 11. Buckling and constrained applied load against crack extension results for LT orientation 12-inch-wide M(T) specimens.

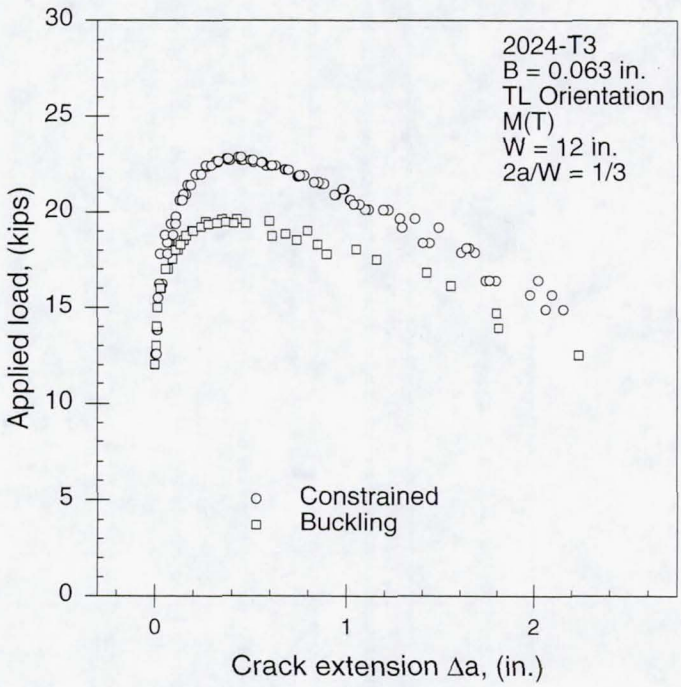


Figure 12. Buckling and constrained applied load against crack extension results for TL orientation 12-inch-wide M(T) specimens.

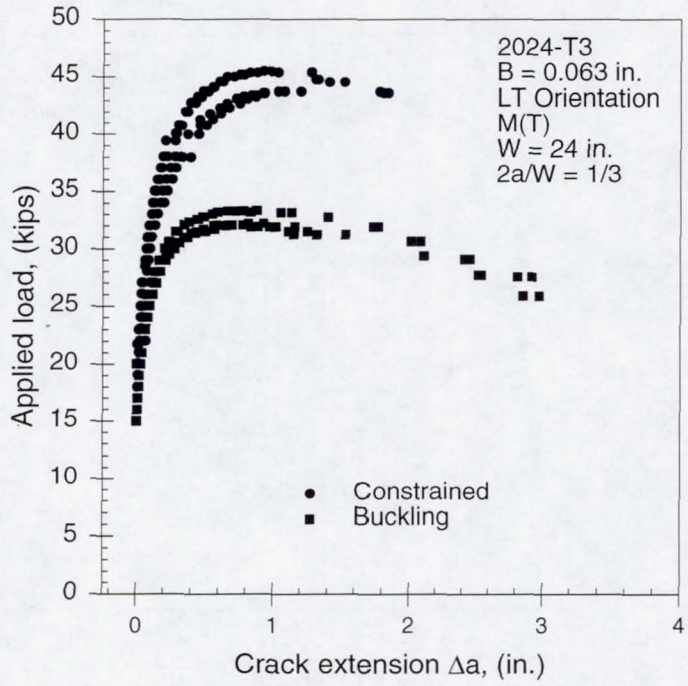


Figure 13. Buckling and constrained applied load against crack extension results for LT orientation 24-inch-wide M(T) specimens.

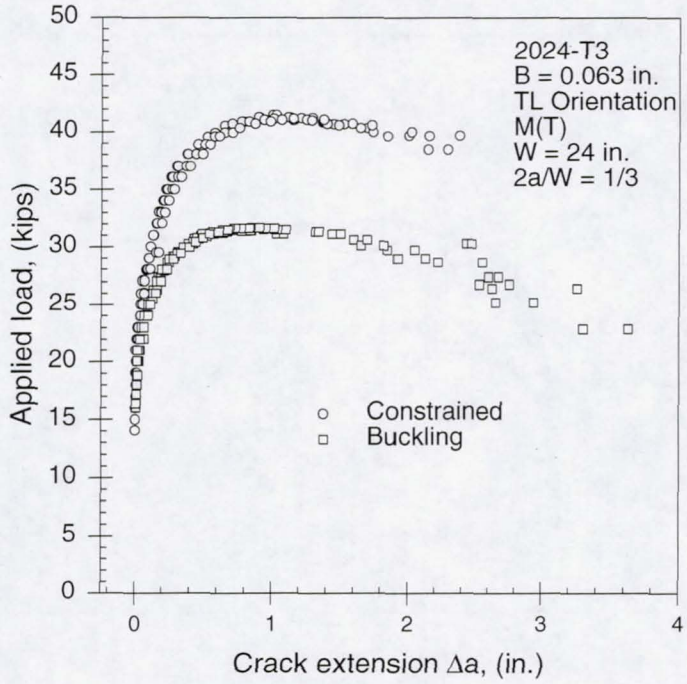


Figure 14. Buckling and constrained applied load against crack extension results for TL orientation 24-inch-wide M(T) specimens.

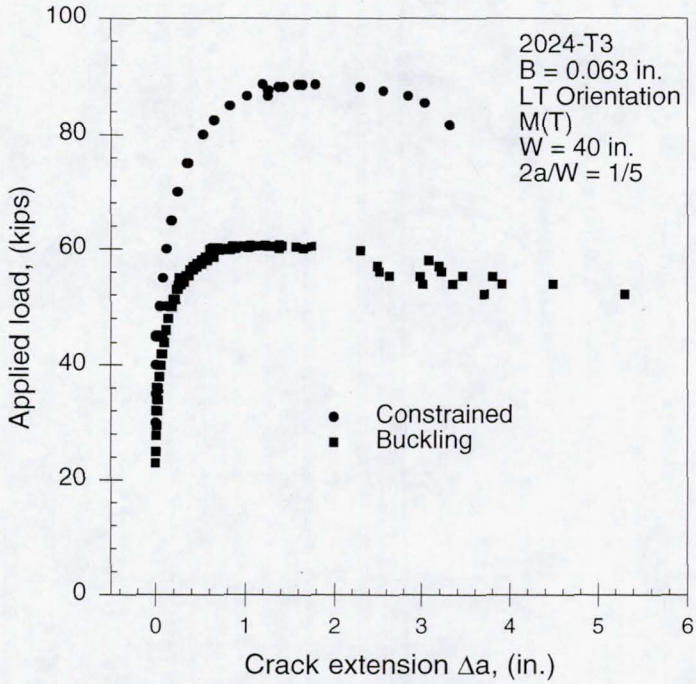


Figure 15. Buckling and constrained applied load against crack extension results for LT orientation 40-inch-wide M(T) specimens (2a/W =0.20).

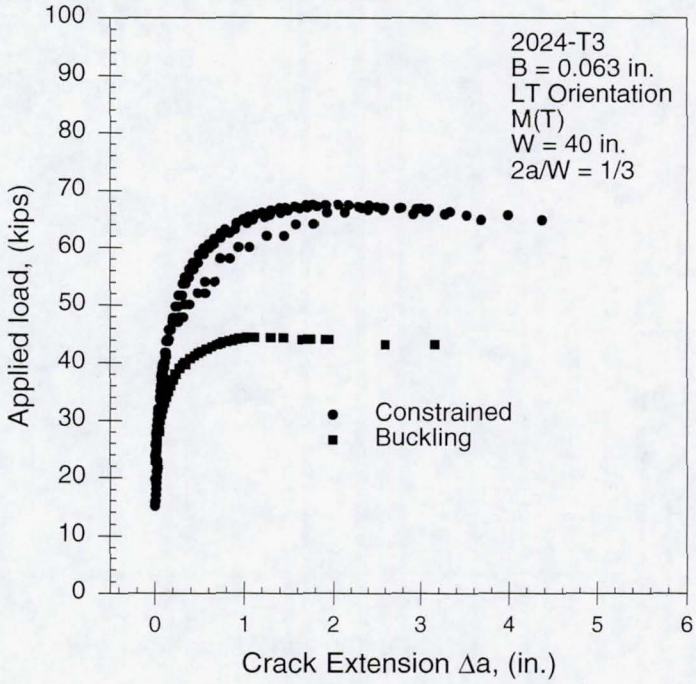


Figure 16. Buckling and constrained applied load against crack extension results for LT orientation 40-inch-wide M(T) specimens (2a/W =1/3).

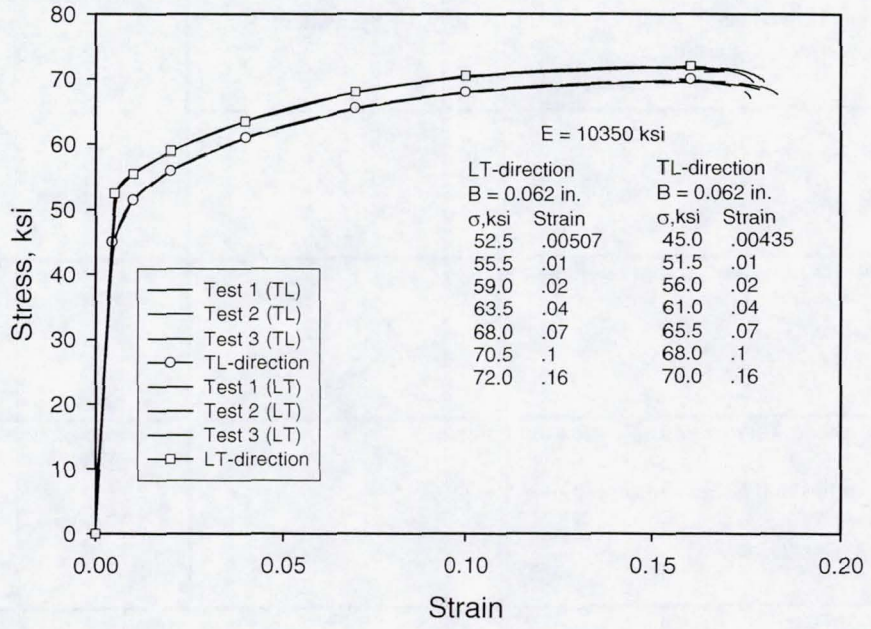


Figure 17. Tensile results for 2024-T3 aluminum alloy results.

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13. ABSTRACT (Maximum 200 words)
A series of fracture test were conducted to determine the effects of specimen type, specimen width and buckling on the fracture behavior of cracked thin sheet (0.063 inch thick) 2024-T3 aluminum alloy. A summary of the experimental measurements is presented for fracture tests conducted on two specimen types and various widths. Middle-crack tension M(T) and compact tension C(T) specimens were tested in the L-T and T-L orientation with duplicate tests for each condition. Four widths (W= 3, 12, 24, and 40 inch) were tested for the middle-crack tension specimens, and three widths (W=2, 4, and 6 inch) were tested for the compact tension specimens. The M(T) specimens were tested in either a constrained (out-of-plane displacements restrained with anti-buckling guides) or unconstrained conditions were the specimen was free to buckle out of plane. Measurements were made of load against crack extension for all specimens.

14. SUBJECT TERMS
Fracture tests; Compact tension; Center crack tension; 0.063 inch thick 2024-T3; Crack extension; Fracture toughness; Tensile properties; Buckling

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