FRACTURE TOUGHNESS OF MULTIPLY LAYER ADHESIVE BONDED ALUMINIUM ALLOY SHEET

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Summary

The fracture toughness of multiply adhesive bonded aluminium alloy sheet is superior to solid material of the same alloy. The relative increase in fracture toughness of M.A.B. material compared to solid is higher for materials with a low fracture toughness. For 2024-T3 a gain was recorded of 25% and for 2024-T8 the difference was 50%.
The specific strenght of compact tension specimens showed no influence of the total amount of sheets, provided no buckling effects are present. The type of adhesive used for structural bonding has a negligible effect on toughness. If however, high modulus fibres are incorporated in the bondline of M.A.B. material again an increase in fracture toughness was observed of about 30% compared to normally M.A.B. material.

1. INTRODUCTION

One of the advantages of adhesive bonded metal to metal structures is the high resistance to crack propagation and high residual strength as compared to integrally machined parts.

In an aircraft the lower wing skin panels are critical as to fatigue due to cyclic tensile stresses during flight operation. Materials are selected with a high resistance to crack propagation and high fracture toughness to improve residual strength and fail safe properties.
To improve the crack tolerance properties of fatigue critical constructions, Multiply Adhesive Bonded (M.A.B.) structures can be used as an alternative to solid metal machined parts, because thin sheet material shows a higher fracture toughness compared to solid material of the same composition and a higher fatigue crack resistance under flight conditions due to retardation effects. Further improvements may be obtained if the adhesive film is reinforced with high modulus material such as Aramid and Carbon fibres.

In the investigation reported here a comparison is made between M.A.B. and solid test specimens of various aluminium alloys as to the fracture toughness properties.

2. THEORETICAL BACKGROUND OF FRACTURE TOUGHNESS

The fracture toughness of materials is expressed in the critical stress intensity factor described by Fracture Mechanics, developed as an additional design concept, where conventional design criteria, such as tensile strength, yield strength etc., are insufficient for high strength materials. Fracture toughness is based on the strength of cracked materials. If a structural cross-section is reduced due to cracking, the load carrying capability is decreased more than proportional in high strength materials. High stresses at the crack tip, developed due to lack of plastic deformation, cause unstable crack growth if the stress intensity reaches a critical level, depending on the material properties and the crack length.

$$K_I = \sigma \sqrt{\pi . a} \qquad (1)$$

σ is the gross stress in the panel of infinite width.
2a is the crack length
K_I is the stress intensity factor in the cleavage mode

If K_I increases due to increasing stress or increasing crack length it reaches its critical value, K_{IC}, and unstable crack growth will occur.
K_{IC} can be considered as a material property and is a measure of the crack resistance of the material, called the plane strain fracture toughness. The value of K_{IC} is reached if sufficient material around the crack tip will refrain it from plastic deformation. If plastic deformation occurs a higher stress intensity is needed for crack propagation. This is the case if the crack front is small as in thin sheets.
A shear mode crack occurs and the critical stress intensity value is called the plane stress fracture toughness. K_C, which cannot be considered as a real material property, because it depends on the amount of plastic deformation which can develop depending on the material thickness and size of the part for a certain type of alloy.

The superior fracture toughness value of M.A.B.-metal structures is based on this thickness effect related to the gradual transition from fully plane strain to fully plane stress.
If the size of the plastic zone around the crack tip is of the order of the sheet thickness, plane stress will develop.
If B is the material thickness while r_p is the size of the plastic zone than K_C defines the residual strength if $r_p/B \geqslant 1$.
K_{IC} rules the residual strength if $r_p/B \ll 1$.
Experimentally it was found that r_p/B 0.025 for a full development of the plane strain condition. Because the plastic zone dimensions are proportional to K_I^2/σ_{ys}^2 a large value of K_I and a low value of σ_{ys} results in a large plastic zone and a higher thickness is needed to maintain the

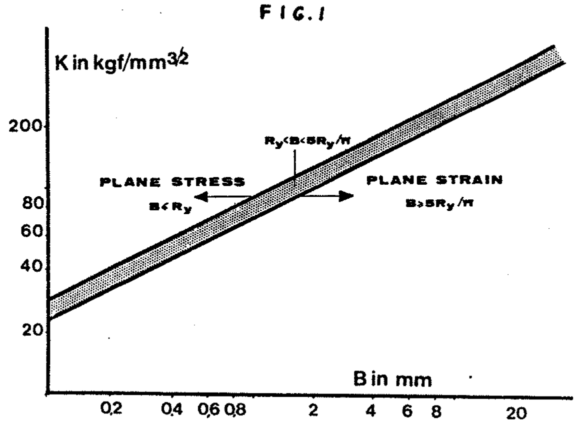
plane strain condition.
The ASTM requirement for plane strain is specified at a thickness of

$$B = 2.5\ K_{IC}^{2} / \sigma_{ys}^{2} \qquad (2)$$

Fatigue crack propagation occurs mostly in the plane strain condition because K_{max} is much lower than K_{IC}. At the end of the crack life a transformation from plane strain to plane stress values takes place changing the crack from a cleavage mode to a shear mode, if K_C defines the residual strength.

In figure 1 the transition zone between plane stress and plane strain is given for 2024-T3 and 7075-T6.

FIG.1



To measure the fracture toughness the Compact Tension specimen is used in case of thick materials, while the Central Notched specimen is used if thin sheets are to be measured.

2.1 The Compact Tension test specimen

In figure 2 the Compact Tension specimen is shown as specified by ASTM E-399-72 (1).

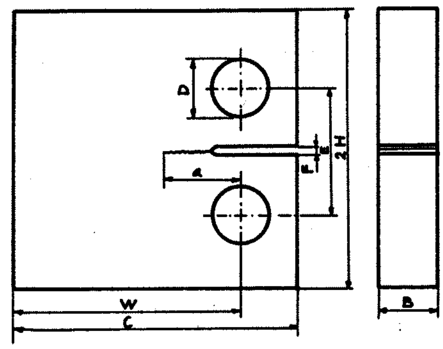
At a tensile force P the stress intensity is induced at the crack tip due to the moment P x a.

$$K_I = \frac{P\sqrt{a}}{B\ .\ W}\ .\ f^{*}(a/W) \quad \text{or}$$

$$K_I = \frac{P}{B\sqrt{W}}\ .\ f\ (a/W) \qquad (3)$$

The function f^{*} (a/W) depends on the dimensions of the specimen.

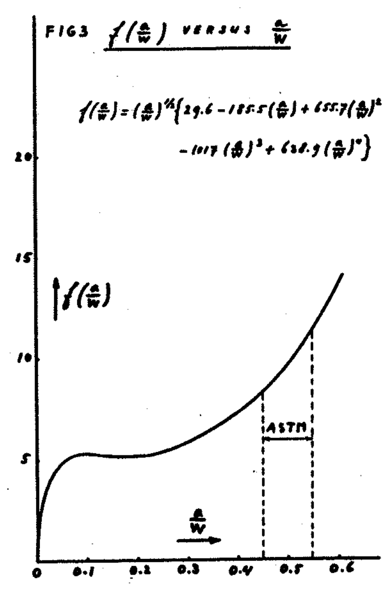
The requirements are H/W = 0.6 and
$0.45 < a/W < 0.55$
(lit. 2)



	DIMENSIONS mm
a	CRACKLENGTH
B	SPECIMEN THICKNESS
C	100.0
D	19.25
E	44.0
F	2.0
2H	96.0
W	80.0

FIG.2 COMPACT TENSION SPECIMEN

It is more practical to incorporate $(a/W)^{\frac{1}{2}}$ into the function f^{*} (a/W).
This function $f\ (a/W) = (a/W)^{\frac{1}{2}}\ f^{*}\ (a/W)$.
In figure 3 the factor f (a/W) is given versus the relative crack length a/W.



For H/W = 0.6

$$f(a/W) = (a/W)^{\frac{1}{2}} \left\{ 29.6 - 185.5(a/W) + 655.7\ (a/W)^{2} - 1017\ (a/W)^{3} + 638.9(a/W)^{4} \right\} \qquad (4)$$

The values of f(a/W) for some typical values of a/W are given in table 1.

Table 1

f(a/W) for some typical values of a/W.

a/W	f(a/W)
0.1	5.2664
0.2	5.1940
0.3	5.4849
0.4	7.3237
0.5	9.6034
0.6	13.5411

If the requirements of the ASTM specification cannot be met for a valid K_{IC} value the crack intensity K_Q is only a reduced representation of the tensile force needed to fracture the specimen. As in most cases of ductile material this K_Q-value is still dependent on the relative crack length it is more practical to reduce the tensile force to crack the specimen, by dividing it by the specimen thickness B at a given a/W value.

2.2 Center Notched Tensile Test specimen

In fact the C.N.T. specimen is a representation of a crack in a stress field, however, in a sheet with finite dimensions, shown in figure 4.

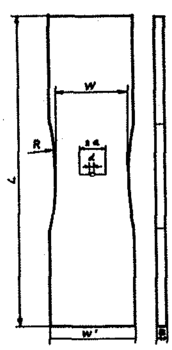


FIG 4 CENTER NOTCH TENSILE TEST SPECIMEN

The basic formula to calculate the stress intensity factor is

$$K = \sigma \sqrt{a} . f(2a/W) \qquad (5)$$

The correction factor for finite dimensions is given as

$$f(2a/W) = 1.77+0.22(2a/W)-0.51(2a/W)^2+ 2.7(2a/W)^3 \qquad (6)$$

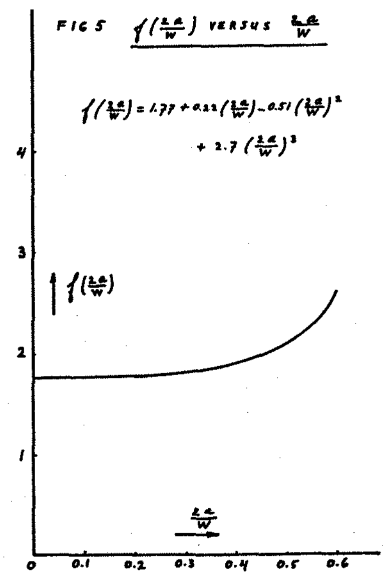
The requirements given by Fedderson for a valid K_C value are

$$2\ a/W \leq 1/3 \text{ and}$$
$$\sigma_c < (2/3)\ \sigma_{ys}$$

Minimum specimen width:

$$W_{min} = (27/2\pi)(K_C/\sigma_{ys})^2 \qquad (7)$$

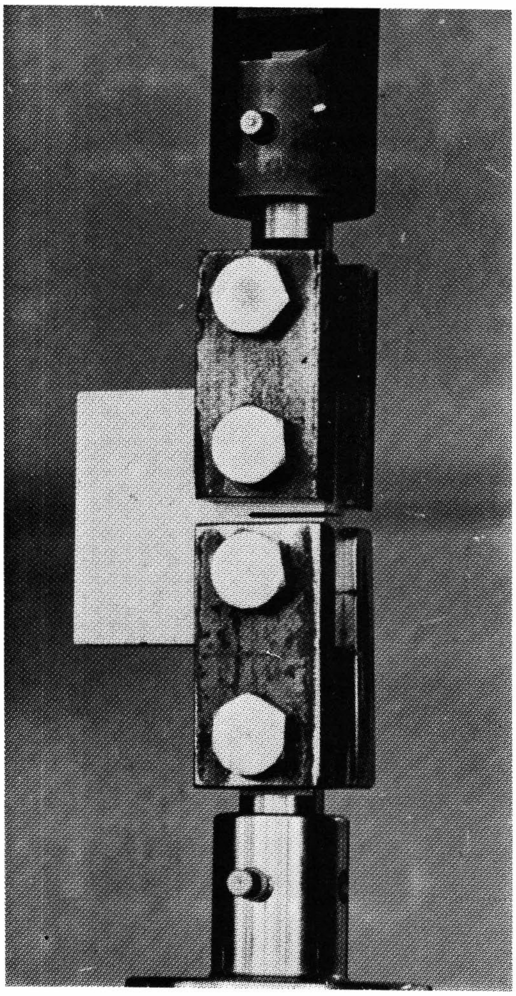
The relation between f(2a/W) and 2a/W is given in figure 5.



3. EXPERIMENTAL PROCEDURE

For fracture toughness testing the compact tension test specimen was chosen because large material thicknesses are needed to develop plane strain conditions. All dimensions except the specimen thickness and crack length were kept constant, because the ASTM requirements of B in relation to W cannot be met for thin sheets. No valid K_{IC} values can be expected for this reason and if calculations are carried out the stress intensity factor will be "K_Q".

The specific strength P/B is given as a measure of the residual strength in relation to a/W.
Every configuration is tested with different a/W values and plotted against P/B. Out of these plots the P/B values at a/w = 0.2, 0.3, 0.4 and 0.5 were interpolated to carry out the comparison between configurations. All specimens were fatigue precracked prior to final testing, according to ASTM requirements.
The fixture that was used in the Tensile Testing Machine is shown in photograph 1.



figures 6 a through g.
Interpolation to a/W = 0,2-0,3-0,4-0,5 was carried out and these values are presented in table 3.

Table 3

	B mm \ a/W	P/B kgf/mm 0.2	0.3	0.4	0.5	K_Q kgf/mm$^{3/2}$ 0.2	0.3	0.4	0.5
2024-T3	5	436	336	250	184	252	221	205	197
	10	450	352	258	182	261	232	212	195
	16	408	310	228	166	236	205	187	178
	20	368	288	222	158	213	190	182	169
	26	370	294	224	156	215	194	184	167
	42	357	280	214	156	207	185	175	167
	nx1	450	360	272	196	261	238	223	209
2024-T8	5	272	216	166	126	157	143	137	135
	10	240	182	138	100	139	120	113	107
	16	198	156	118	84	114	103	97	90
	20	188	147	112	81	109	97	92	87
	26	198	152	118	90	114	100	97	96
	42	208	170	130	94	120	112	107	100
	nx1	310	248	192	140	180	164	157	150

3.1 Comparison of multiply layer adhesive bonded panels and solid material

Test specimens were prepared from 2024-T3 and 2024-T8 material with a high resp. a low fracture toughness.
The following configurations were investigated:

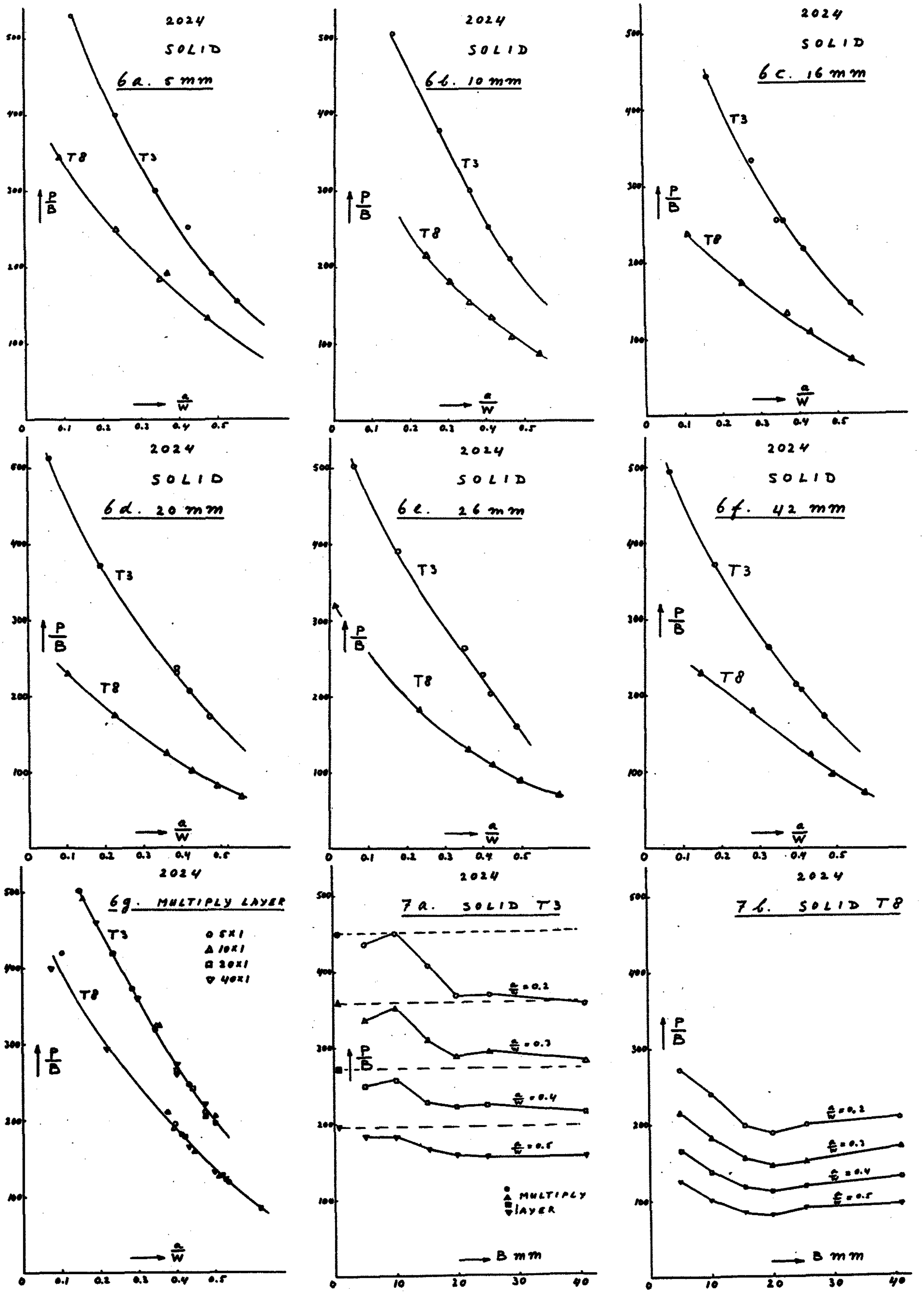
Table 2

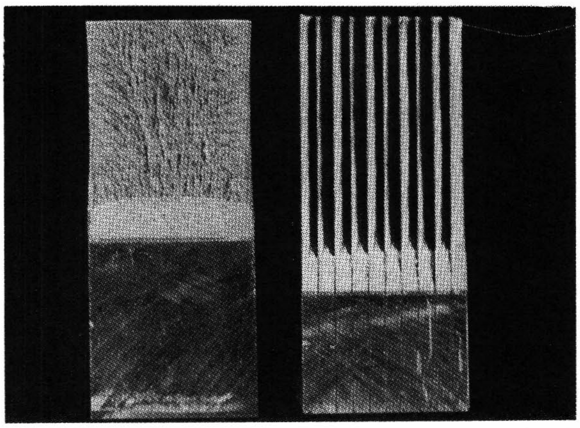
Multiply adhesive bonded clad sheet	Solid
5 x 1 mm	5 mm
10 x 1 mm	10 mm
20 x 1 mm	16 mm
40 x 1 mm	20 mm
	26 mm
	42 mm

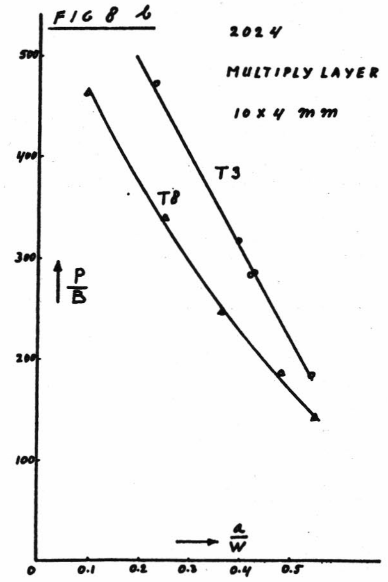
From each configuration 6 specimens were prepared with different crack dimensions. After fatigue precracking the specimens were tensile tested until fracture. The maximum recorded load was taken as the value for residual strength. To make comparison possible, the specific ultimate load was divided by the specimen thickness. All test data are graphically presented in figures 6 a through g.

The value of K_Q was obtained by using formula 3 of section 2. The P/B value in relation to the material thickness is presented in figure 7 a for 2024-T3 material and figure 7 b for 2024-T8 alloy. The values of multiply adhesive bonded panels are independent of the amount of sheets in the specimen and are shown in the graphs for 1 mm thickness.
It is obvious that the residual strength of multiply adhesive bonded panels for all values of a/W, is superior to the solid material. The highest gain in fracture toughness is found if solid material with a thickness of 20 mm or higher is compared with multiply adhesive bonded material.
The replacement of solid material of a low toughness by multiply adhesive bonded material is more effective, compared to material with a high toughness.
For 2024-T3 a gain of 25% is recorded.
For 2024-T8 a gain of 50% is found.
This reflects the possible weight savings by multiply adhesive bonding based on equal residual strength values.

On photograph 2 the fracture mode is shown for a solid and for a M.A.B. specimen.


2024
SOLID
6a. 5 mm
T3
T8
P/B
a/W
2024
SOLID
6b. 10 mm
T3
T8
P/B
a/W
2024
SOLID
6c. 16 mm
T3
T8
P/B
a/W
2024
SOLID
6d. 20 mm
T3
T8
P/B
a/W
2024
SOLID
6e. 26 mm
T3
T8
P/B
a/W
2024
SOLID
6f. 42 mm
T3
T8
P/B
a/W
2024
6g. MULTIPLY LAYER
T3
T8
5X1
10X1
20X1
40X1
P/B
a/W
2024
7a. SOLID T3
a/W = 0.2
a/W = 0.3
a/W = 0.4
a/W = 0.5
MULTIPLY LAYER
P/B
B mm
2024
7b. SOLID T8
a/W = 0.2
a/W = 0.3
a/W = 0.4
a/W = 0.5
P/B
B mm



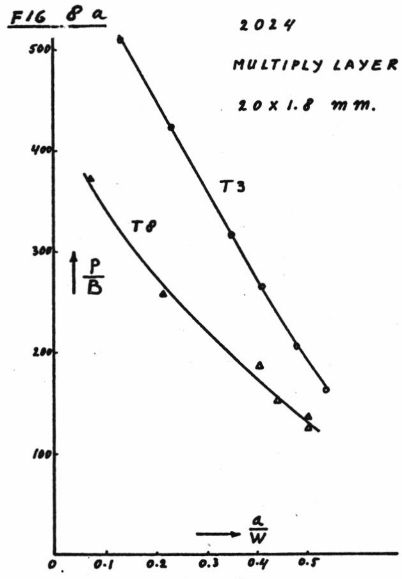


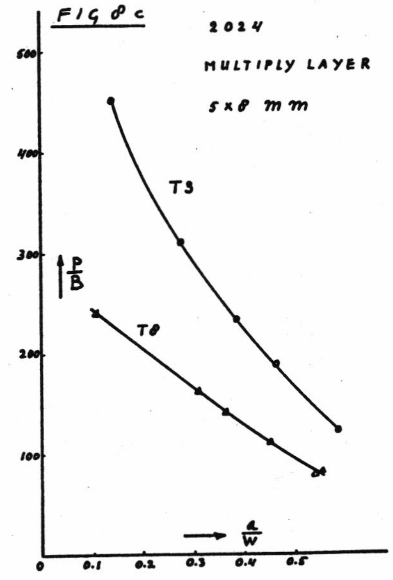
3.2 The effect of sheet thickness in multiply adhesive bonded material

Composite material was prepared with a total thickness of about 40 mm by means of adhesive bonding. The following configurations were investigated:

40 x 1 mm, 20 x 1.8 mm, 10 x 4 mm,
5 x 8 mm and 1 x 42 mm,

The results are graphically presented in figure 8. (see figure 6 g for 40 x 1 mm and figure 6 f for 1 x 42 mm).





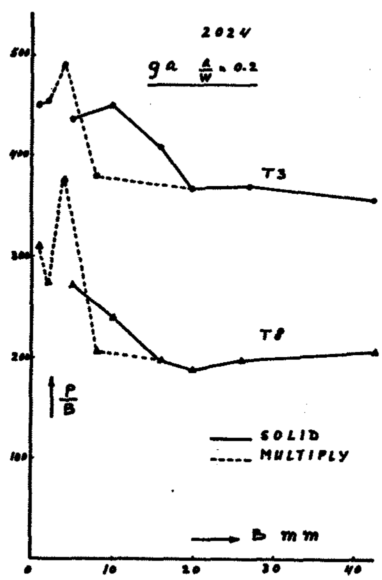
Interpolation to a/W of 0.2 - 0.3 - 0.4 - 0.5 produces the values of P/B as shown in table 4.

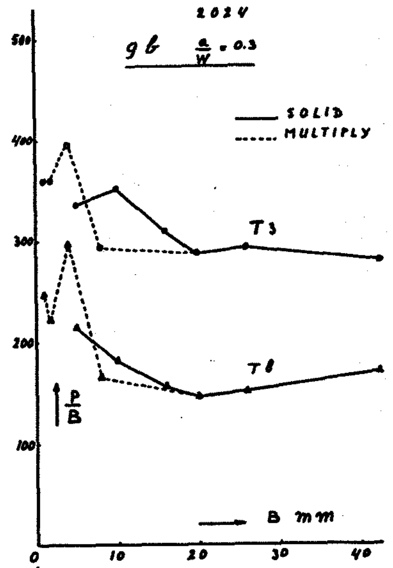
Table 4

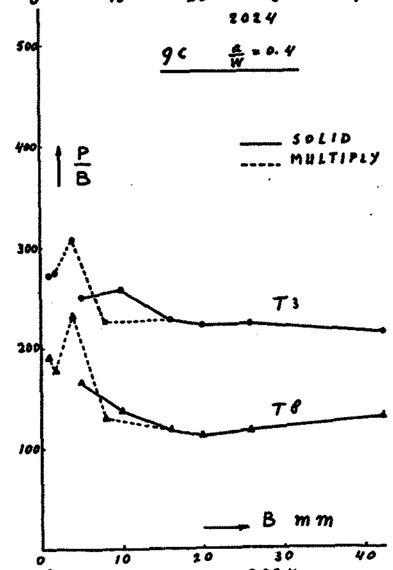
The influence of sheet thickness on residual strength

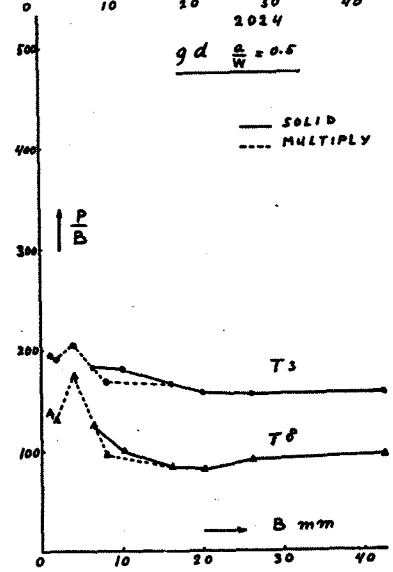
MAT	a/W / Configuration	P/B in kgf/mm 0.2	0.3	0.4	0.5
2024-T3	40 x 1	450	360	272	196
	20 x 1.8	454	360	274	192
	10 x 4	490	396	308	206
	5 x 8	380	294	226	170
	1 x 42	357	280	214	156
2024-T8	40 x 1	310	248	192	140
	20 x 1.8	274	222	176	132
	10 x 4	376	298	232	176
	5 x 8	206	166	130	96
	1 x 42	208	170	130	94

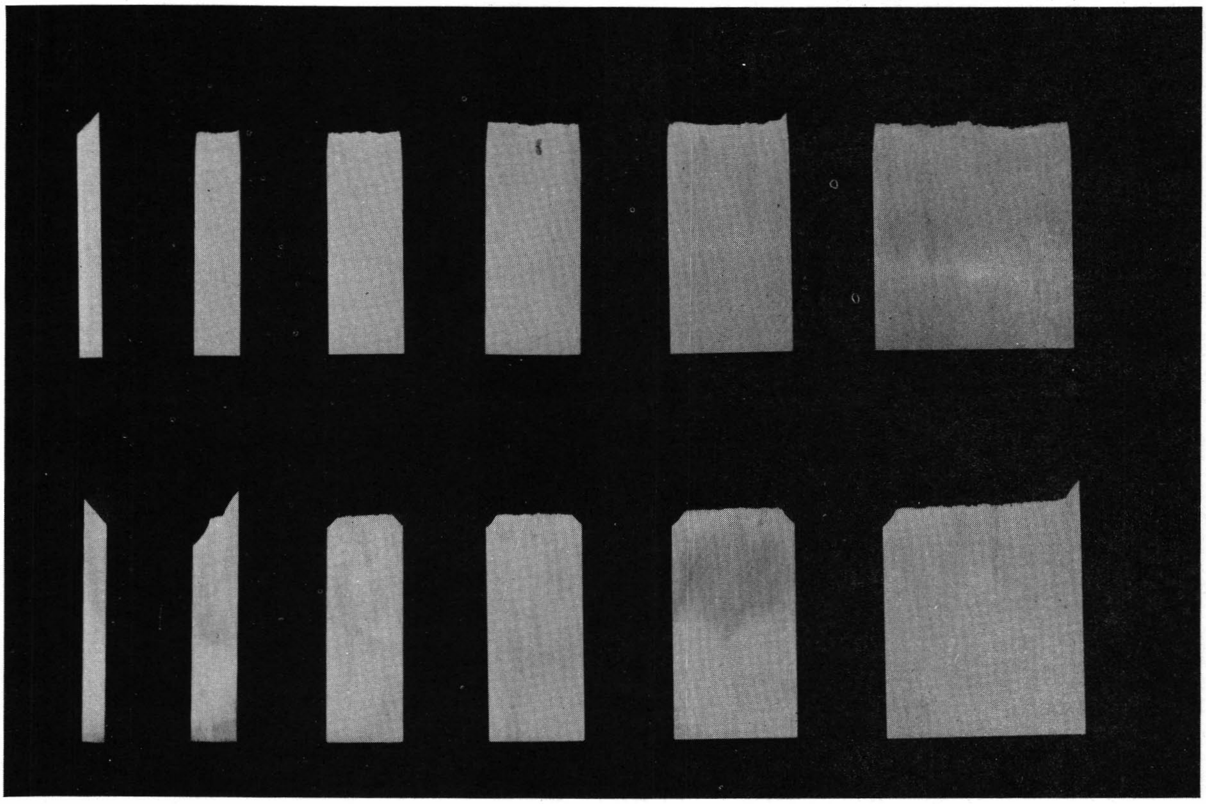
The optimal results were found for 10 x 4 mm multiply adhesive bonded panels. The 5 x 8 mm panels showed a residual strength practically equal to that of solid metal of 42 mm. Single sheets of 5 and 10 mm were recorded to have higher values of P/B. This result may need more investigation. An explanation cannot be given.
In figure 9 all values of multiply adhesive bonded panels and solid material are summarized for an a/W value of 0.2.

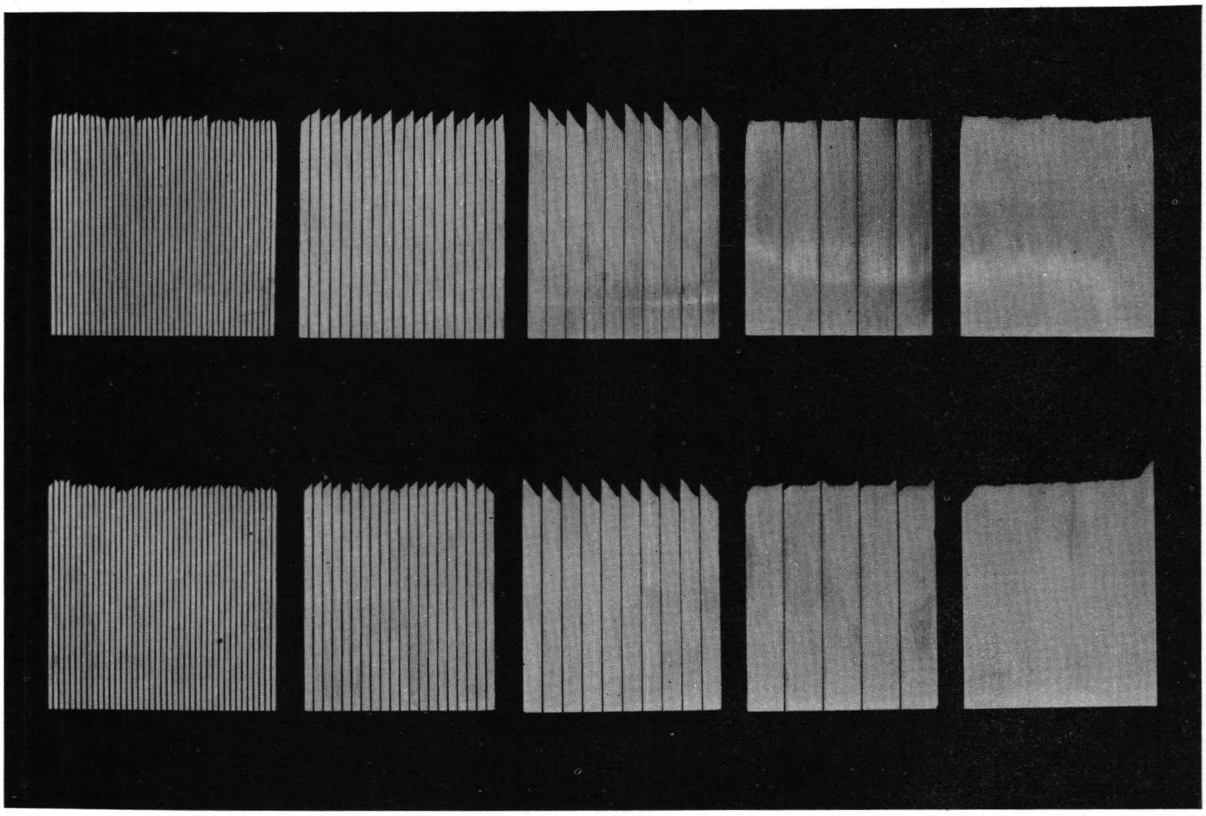












On photograph 3 the fracture modes of solid metal are shown. Ductile 2024-T3 on the top side with clearly visible necking near the fracture surface. Brittle 2024-T8 on the lower side with cleavage mode and shear lips.
Note the second panel with large shear lips.
On photograph 4 the fracture mode is shown of M.A.B. panels with decreasing sheet thickness. The ductile material shows the same fracture mode as the single sheets (topside).
The brittle material shows the same fracture mode as single sheets except the 5 x 8 mm M.A.B. panel which shows a more brittle behaviour as was found on single sheets of 10 mm. No explanation can be given of this phenomenon.

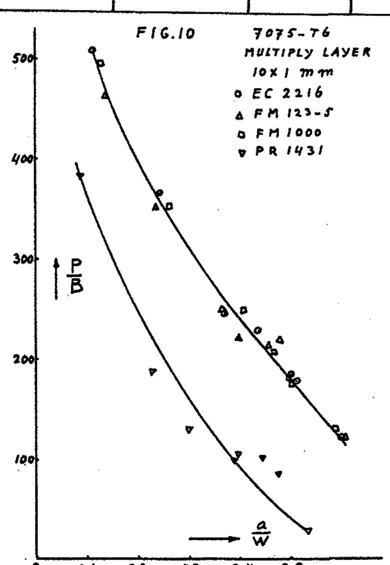
3.3 The effect of the adhesive on residual strength

The effect of the adhesive on the residual strength of multiply adhesive bonded specimens was measured on 7075-T6 with structural adhesives with and without high modulus fibre reinforcement. The results are graphically recorded in figure 10. The interpolated values for a/W = 0.2 - 0.3 - 0.4 - 0.5 are shown in table 5.

Table 5

The effect of adhesives on residual strength of M.A.B. panels. Values of P/B in kgf/mm

	P/B in kgf/mm			
Adhesive \ a/W	0.2	0.3	0.4	0.5
FM 1000	412	325	252	188
EC 2216	400	314	242	180
FM 123-5	392	298	242	164
PR 1431	250	160	94	42



No significant influence of the adhesive was found if structural adhesives are used without reinforcement. The low results for PR 1431 (sealing compound) are due to buckling effects during fracture toughness testing.

3.4 The effect of the sheet materials

From the previous paragraphs the values of P/B for 1 mm sheet multiply adhesive bonded panels of different materials are summarized in table 6.

Table 6

Specific strength of multiply adhesive bonded panels of different materials. Values of P/B in kgf/mm.

	P/B in kgf/mm				
Material \ a/W	0.2	0.3	0.4	0.5	δ_2 (%)
2024-T3 solid	357	280	214	156	
2024-T3 MAB	450	360	272	196	18.5
7075-T6 solid	N.A.	N.A.	N.A.	N.A.	
7075-T6 MAB	392	298	242	164	15.0
2024-T8 solid	208	170	130	94	
2024-T8 MAB	310	248	192	140	5.0

N.A. Not available as C.T. results with specimens of same dimensions

As can be expected the material with the lowest ductility shows the lowest fracture toughness values.
From these results it can be concluded that based on fracture toughness 2024-T3 solid can be replaced by 7075-T6 MAB material.

3.5 The effect of reinforcements in the adhesive layer

To investigate further improvements of multiply adhesive bonded material, panels were adhesive bonded with unidirectional carbon fibres to compare with FM 123-5 adhesive bonded panels and solid material of 5 mm thickness.
The results are given in figure 11 as P/B values against relative cracklength a/W.
The interpolated values for various a/W are given in table 7.

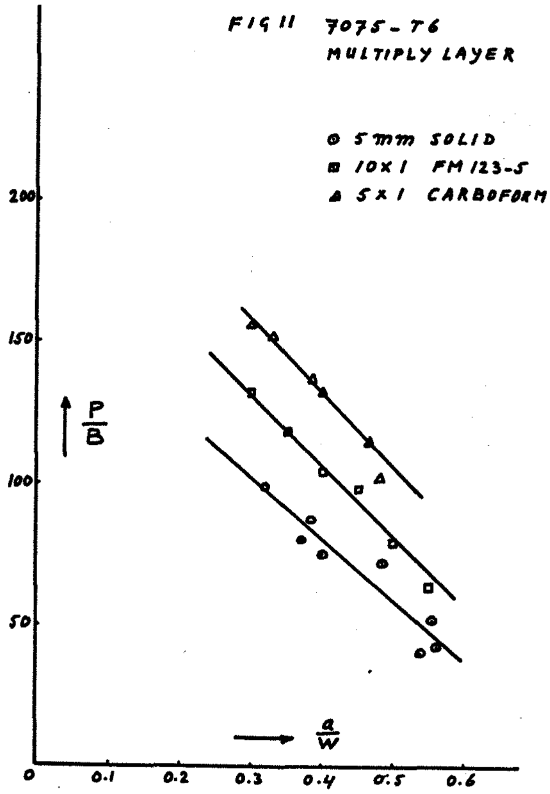


Table 7

P/B versus a/W for solid and multiply reinforced adhesive bonded 7075-T6.

	P/B in kgf/mm			%
a/W / Configuration	0.3	0.4	0.5	0.5
Solid 5 mm	103	81	55	100
10 x 1 FM 123-5	132	104	78	142
5 x 1 Carbon	158	130	102	185

A significant improvement of the specific strength is obtained using Carboform as an adhesive. This increase is about 30% compared to FM 123-5 adhesive bonded panels at an a/W value of 0.5.

Fracture toughness tests with M.A.B. material with and without reinforced adhesives were carried out using Center Notched Tensile specimens. A summary of the testresults is given in table 8.

Table 8

K_C values for M.A.B. panels 3 x 1 mm

Configuration	K_C kgf/mm $^{3/2}$	
	2024-T3	7075-T6
FM 123-5	123.2 (100)	131.7 (100)
Aramid	131.6 (107)	151.3 (115)
Carbon	162.4 (132)	176.6 (134)

Again an increase of about 30% is recorded for Carboform adhesive bonded sheets of 1 mm thickness.
Aramid in the adhesive layer showed an improvement of 7 to 15%.

3.6 Conclusions from Fracture Toughness Tests

From all previous results the next review can be obtained in relative values at a/W = 0.5.

Table 9

Relative P/B values for all tested materials

	2024-T3			7075-T6			2024-T8
Solid	100			100			100
FM 123-5	126	100		141	100		149
Aramid	134	107	100	162	115	100	-
Carbon	166	132	123	188	133	116	-

The following conclusions can be drawn:

1. M.A.B. results in higher fracture toughness, increasing the residual strength of cracked components.
2. The relative improvement due to M.A.B. is higher for materials with a low fracture toughness than for materials with a high fracture toughness.
3. The relative improvement due to reinforcement of the adhesive layer is equal for materials with a low and a high fracture toughness.
4. The optimal sheet thickness for M.A.B. seems to be around 4 mm for 2024-T3 and 2024-T8 material.
5. The amount of sheets does not influence the fracture toughness.

ACKNOWLEDGEMENT

For the preparation of this paper, Fokker reports were used prepared by A.H. LaCrois, J. Koning and D.T. Kolijn. I am very grateful for their help on this subject.

LITERATURE ON FRACTURE TOUGHNESS

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