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Impact Damage Resistance of Various Fibre Metal Laminates

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Abstract: The impact damage resistance of Fibre Metal Laminates (FML) is studied. FML is a new family of laminated materials which consist of thin aluminium layers bonded together by intermediate fibre/epoxy layers. Different glass fibre FML variants are compared with Al 2024-T3, and carbon/PEI composites. The effect of the relative glass/epoxy content in FML is determined. FML shows an equal to 15% better minimum cracking energy at low velocity impact compared to monolithic aluminium, but behaves much better (2-3.5x higher minimum cracking energy) at high velocities. The impact damage resistance of FML increases with an increasing glass/epoxy content. This is partly due to the strain rate sensitivity of the glass fibres. FML are also superior because during impact delamination occurs, and the laminae consequently will be loaded in a more efficient membrane deformation compared to the dominant bending deformation of the monolithic material. Carbon/PEI thermoplastic composites have a poor impact damage resistance.

Résumé: La résistance aux dégâts de percussion de Fibre Metal Laminates (FML) est étudiée. Les FML sont une nouvelle famille de matériaux lamellés, qui consistent de lamelles d'aluminium collées les unes contre les autres par des couches intermédiaires de fibres/époxy. Plusieurs sortes de FML de fibres de verre sont comparées à Al 2024-T3, et à des composites carbon/PEI. L'effet du contenu relatif verre/époxy dans les FML est déterminé. A percussion à basse vitesse, les FML montrent une énergie minimum d'éclatement égale ou 15% meilleure comparés à l'aluminium monolithe, mais à vitesses élevées les FML se comportent beaucoup mieux (une énergie minimum d'éclatement 2-3.5× plus élevée). La résistance aux dégâts de percussion des FML augmente avec le rapport verre/époxy. Ceci est due partiellement à la sensitivité des fibres de verre à la vitesse de contrainte. Les FML sont aussi supérieurs car pendant la percussion les lamelles se détachent, et par conséquence les FML seront chargés dans une déformation de membranes qui est plus efficace que la déformation de fléchissement du matériau monolithe. Les composites thermoplastes carbon/PEI ont une résistance aux dégâts de percussion peu élevée.

1. INTRODUCTION

Fibre Metal Laminates (FML) are a family of highly fatigue resistant laminated materials which were developed at Delft University [1-6]. The laminates consist of thin 0.2-0.5 mm high-strength aluminium alloy sheets bonded together with fibre/adhesive prepreg layers. The prepregs can be aramid, carbon or glass fibres embedded in an epoxy adhesive. FML's were developed as material with a high fatigue resistance, achieved by fibre bridging (see Fig.1).If a crack has initiated in the aluminium alloy sheets, some limited delamination will occur at the interfaces between the epoxy resin and the fibres. This controlled delamination makes a stress redistribution from the metal to unbroken fibres in the wake of the crack possible. Crack bridging provided by the strong fibres restrains crack opening and thus reduces the driving force for crack growth in the metal layers. FML's combine the formability and machinability of aluminium alloys with the good fatigue resistance and high specific strength of composite materials

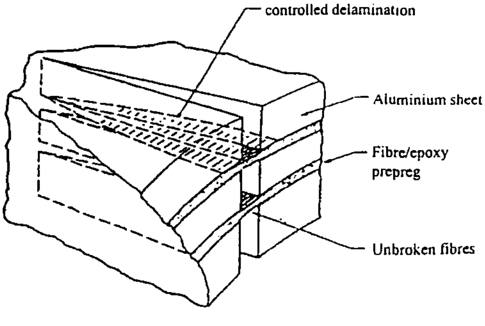

Figure 1: Crack bridging in FML.

After curing, an internal stress system will be present in FML's, i.e., tensile stresses in the aluminium and compressive stresses in the prepreg layers. The material can be post-stretched, which causes a compressive stress in the metal sheets which makes the fatigue properties even better than of the material in the as cured condition. Different types of aluminium alloys are combined with various types of fibres and fibre orientations.

The lay-up determines the thickness of the laminate and is designated with the number of aluminium and prepreg layers, e.g., a 4/3 lay-up consists of four aluminium layers bonded together with three intermediate prepreg layers. The outside layers are always aluminium and shield the prepreg layers from moisture penetration. ARALL was the first generation of FML and is based on aramid fibres. GLARE incorporates S2-glass fibres and is applied for example in the pressure bulkhead of the Lear 45 aircraft and for the Boeing 777 impact critical bulk cargo floor. In this study the impact damage resistance of different types of GLARE is determined and compared with monolithic aluminium and carbon/PEI composites.

2. TESTED MATERIALS

Table 1: List of tested materials with corresponding minimum cracking energies:

Material	*lay-up*	*fibre*	*t (mm)*	*areal density (kg/m^2)*	*minimum cracking energy, low velocity (J)*	*minimum cracking energy, high velocity (J)*
Al 2024-T3	-	-	0.64	1.67	31.8	31.0
	-	-	1.02	2.78	28.1	48.7
	-	-	1.60	4.45	23.5	43.2
	-	-	2.03	5.56	22.4	49.8
	-	-	2.54	6.95	35.6	78.6
	-	-	3.18	8.62	46.7	
GLARE 3	2/1	S2-glass	0.85	2.16	21.4	43.3
	3/2		1.40	3.49	26.2	69.5
	4/3		1.95	4.82	37.0	110.5
GLARE 5	2/1		1.10	2.66	28.4	70.9
	3/2		1.90	4.46	44.1	99.0
	4/3		2.70	6.31	56.9	
GLARE 5Y	2/1		1.35	3.15	28.6	110.5
	3/2		2.40	5.47	52.2	
GLARE 5YY	2/1		1.60	3.65	34.0	126.7
	3/2		2.90	6.46	57.7	
GLARE 3E	2/1	E-glass	0.85	2.18	14.0	27.7
	3/2		1.40	3.52	13.7	47.5
	4/3		1.95	4.86	24.0	
carbon/PEI	$[0/90]_7$	carbon	2.00	3.46	3.8	3.0

Table 1 gives a list of tested materials. GLARE 3 is a FML with Al 2024-T3 and two cross-plied $(0^0/90^0)$ S2-glass/epoxy layers in each prepreg layer, e.g., the GLARE 3 in a 3/2 lay-up is:

$[2024\text{-}T3/0^0/90^0/2024\text{-}T3/90^0/0^0/2024\text{-}T3]$

The thickness of all Al 2024-T3 layers is 0.3 mm. All separate unidirectional S2-glass/epoxy layers have a thickness of 0.1 mm and a fibre volume content of 55%.

Tested derivatives are GLARE 3E in which E-glass is applied instead of S2-glass, and GLARE 5 in which each prepreg layer consists of a cross-ply of *four* instead of two S2-glass fibre layers, e.g., a GLARE 5 in a 3/2 lay-up is:

[2024-T3/0°/90°/0°/90°/2024-T3/90°/0°/90°/0°/2024-T3]

In the same way GLARE 5Y and GLARE 5YY are FML types with per prepreg *six* and *eight* S2-glass fibre layers respectively. Also carbon/PEI thermoplastic composites were tested, with T800H fibres of Torayca in a Polyetherimide (PEI) matrix with a fibre volume percentage of 56%.

3. TEST SET-UP

All impact and static indentation tests were performed with a hemispherical tipped impactor (diameter 15 mm). Square samples with a size of 125x125 mm^2 were clamped between two steel plates with a 100x100 mm^2 opening and were hit in the centre. A constant torque of 40 Nm was applied on 8 bolts which held the test area in a clamped condition. Ten specimens for each material were tested for each velocity regime with impact energies close to the minimum impact energy which created the first crack in the material. In this way the minimum cracking energy could be determined with an accuracy of approximately ±5%.

All low velocity impact tests were performed with a drop weight impact tester with a maximum velocity of 10 m/s and an impactor mass of 2080 g. The impact velocity was determined and the force was measured during impact and processed by computer. The impactor was caught after impact to prevent additional damage from a second impact.

The high velocity impact tests were carried out with an air gun with velocities up to 100 m/s. The projectiles were accelerated by the expanding air of a vessel by burning through a membrane. The displacement of the projectile can be measured before and during impact with a laser/line camera system. Steel tip projectiles of 24 g with a tip diameter of 15 mm were used.

4. RESULTS AND DISCUSSION

The impact damage resistance was characterized by the dent depth, the minimum cracking energy and the width of the damaged area. The dent depth of GLARE showed the same trend as of Al 2024-T3. The permanent dent had a depth of approximately 2/3 of the maximum displacement during impact, as is shown in Fig.2. The dent depth of carbon/PEI is very small up to penetration.

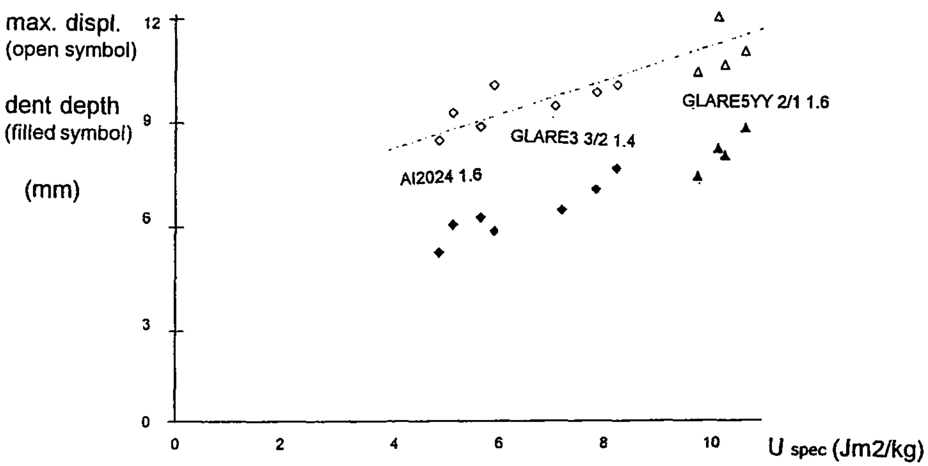

Figure 2: Maximum displacement and dent depth after impact as function of the specific impact energy level.

Minimum cracking energies are given in Table 1 and specific values in Fig.3. No failure of the glass fibres was observed without cracking of the aluminium layers. The first failure at low impact energies was visible as a crack in the outer aluminium layer at the non-impacted side in the fibre direction of FML. At energies somewhat higher than this first cracking energy failure occurred of the aluminium layer at the impacted side and a through crack was created. Fibre failure in the thermoplastic composites also occurred first at the non-impacted side of the specimen but at very low energy levels. In Fig.3 the specific cracking energy is shown, which is the energy divided by the surface density (mass per mm^2). From this figure it can be concluded that these energy levels are higher for high velocity tests. For GLARE this effect is more pronounced than for the other two materials and the effect is increasing with increasing layers of glass/epoxy in FML as is also indicated in Table 2.

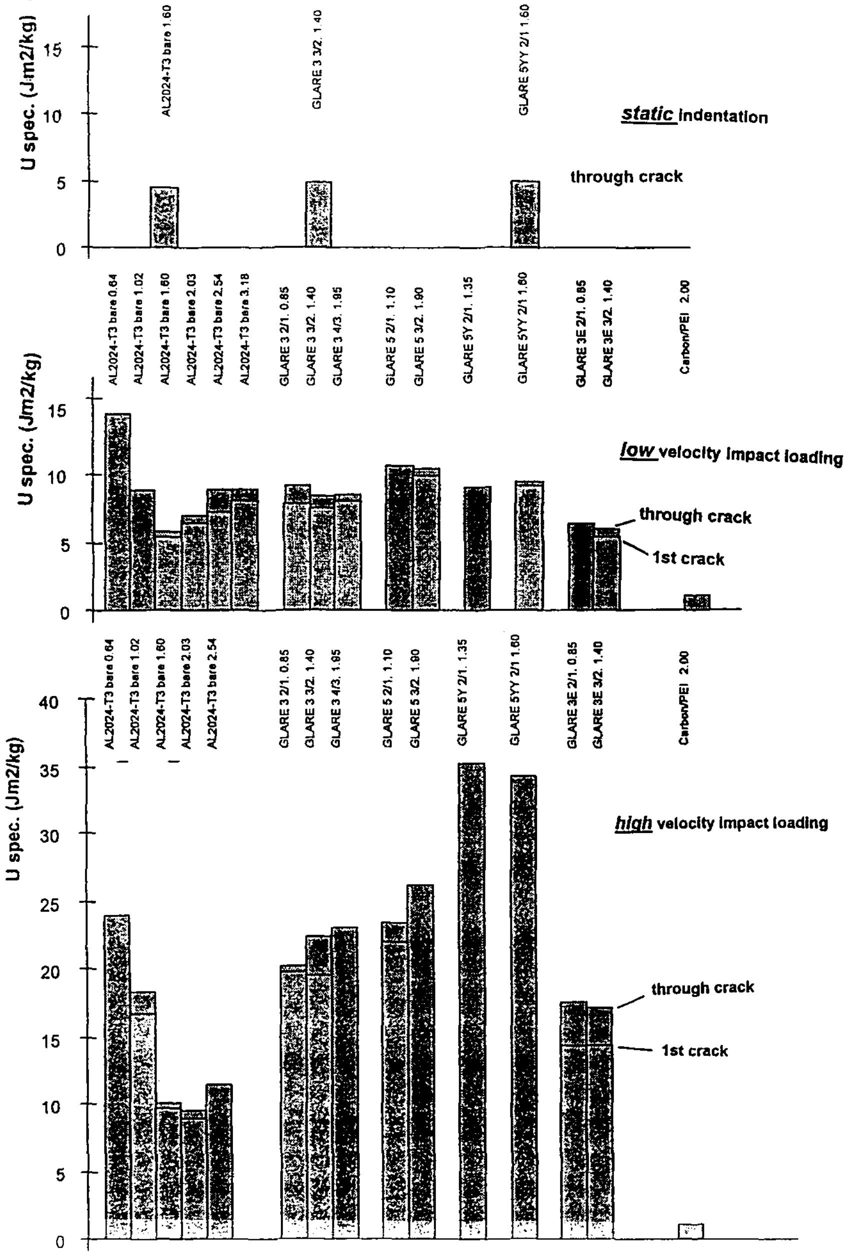

Figure 3: Specific cracking energies.

Table 2: Effect of glass fibre content and velocity regime on minimum cracking energies.

material	specific first cracking energy Jm^2/kg (static)	specific first cracking energy Jm^2/kg (low velocity)	specific first cracking energy Jm^2/kg (high velocity)
Al 2024-T3 1.6 mm	4.4 (dynamic/static ratio=*1.0*)	5.3 (=*1.2*)	9.7 (=*2.2*)
GLARE 3 3/2 1.4 mm	5.0 (dynamic/static ratio=*1.0*)	7.5 (=*1.5*)	19.9 (=*4.0*)
GLARE 5YY 2/1 1.6 mm	5.0 (dynamic/static ratio=*1.0*)	9.3 (=*6.2*)	34.7 (=*6.9*)

The outer aluminium layers of FML were removed by etching which revealed the impact damage in the dent. Three zones could be distinguished: 1. a zone with fibre failure, 2. a delaminated area extending in fibre direction and 3. a zone with cracked epoxy. The total damage width is shown in Fig.4. FML had a smaller damaged area than carbon/PEI and showed less damage when the relative glass/epoxy content of the laminates was increased (GLARE 5YY 2/1 had a smaller damage width than GLARE 3 3/2).

Because the content of glass/epoxy layers in FML showed a large influence on the impact resistance, tensile tests were performed to study the strain rate sensitivity of the GLARE material in comparison with Al 2024-T3. Results are given in Table 3.

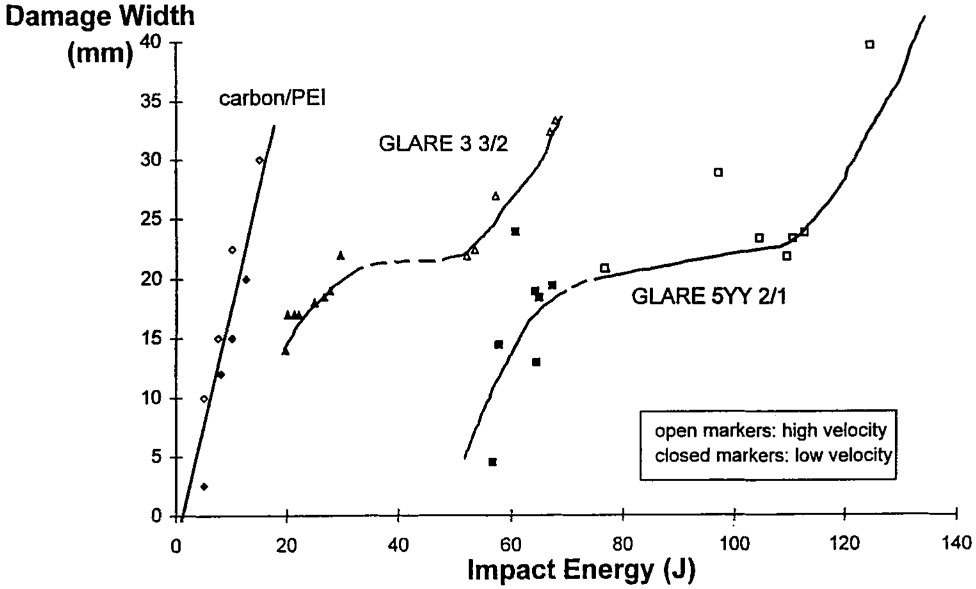

Figure 4: Damage width for carbon/PEI and GLARE.

These results show that the good impact resistance of GLARE is partly due to the strain rate sensitivity of the glass fibres in the material. However, during a tensile test the monolithic aluminium is able to absorb more energy until failure than GLARE. Moreover, the strain rate during an impact event will drop. Therefore a second reason is probably the laminated structure of the FML material. As Fig.2 shows, the thinner aluminium sheets have a higher specific cracking energy level which is due to the more efficient membrane deformation in the thinner sheets compared with the bending behaviour of the thicker materials. The delaminated layers in GLARE will behave more efficiently than an intact laminate or a monolithic sheet.

Table 3: Results of tensile tests at different strain rates.

material	strain rate (s^{-1})	ultimate stress (MPa)	ultimate strain (%)	specific absorbed energy (Jm^2/kg)
2024-T3, t=0.64 mm	$3.3\ 10^{-5}$	501	15.3	6359
	38	480	14.0	6239
	69	472	13.5	5652
GLARE 3 3/2	$4\ 10^{-4}$	666	3.4	1425
	3.8	753	4.3	2039
	38	803	4.8	2428
	69	832	5.5	2898

5. CONCLUSIONS

a. Glass fibre reinforced Fibre Metal Laminates (GLARE FML) show an approximately equal or 15% better specific minimum cracking energy at low velocity impact (10 m/s) compared to monolithic aluminium and is superior (2-3.5x better) at high velocity impact (100 m/s).

b. GLARE FML has a higher minimum cracking energy and a smaller damaged zone if the relative glass fibre/epoxy content of FML is increased. This is partly attributed to the strain rate sensitivity of the glass fibres. FML's with E-glass in inferior to variants with stronger S2-glass fibres.

c. Carbon/PEI composites show a poor impact damage resistance (low minimum cracking energy and large damaged zone) which was not much influenced by the velocity regime.

d. Thin Al 2024-T3 sheets are able to absorb relatively more impact energy because of a more favourable membrane deformation than the more dominant bending behaviour in thicker sheets.

e. This is probably a second reason for the fact that GLARE laminates behave better during static indentation and low and high velocity impact loading. As a consequence of delamination in the impacted area, the laminate will act as a number of separate thin layers in efficient membrane deformation.

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