# LOW VELOCITY IMPACT DAMAGE IN GLARE© FIBRE METAL LAMINATES

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**SUMMARY**: An investigation into the low velocity impact behaviour of GLARE© (GLAss REinforced) fibre metal laminates has been carried out. This study focused on the damage modes and mechanisms through which the panels absorb the energy of impact. Tests were conducted on several variants of GLARE© using an instrumented drop weight impact tower. As the level of impact energy increases the primary damage modes change and the relative amount of absorbed energy also changes. The damage modes are also strongly influenced by the specimen clamping conditions and by the fibre lay up of the panels. Having more fibres in one direction leads to a more predictable and gradual onset of panel penetration.

**KEYWORDS**: low velocity impact, fibre metal laminates, GLARE, delamination damage.

## INTRODUCTION

Development of Fibre Metal Laminates (FMLs) has reached the stage of application to airframes. However, before these materials can be applied to primary structures, more work is needed to gain full understanding of their behaviour under different loading and environmental conditions. A research study examining the low-velocity impact behaviour of GLARE© aluminum laminates is being carried out as part of a joint FML Durability project between Bombardier Aerospace, the Institute for Aerospace Research of the National Research Council of Canada (IAR-NRC) and Carleton University. The project includes a series of impact tests, damage characterization and residual-strength-after-impact tests. An instrumented drop weight impact tower with various impact fixtures and impactor types has been used to generate impact damage. This paper focuses on the impact test results and the relationship between damage formation and energy absorption.

## IMPACT DAMAGE IN GLARE©

### Experimental Procedure

*Materials Tested*

Three variants of glass-reinforced aluminum laminates were tested under the product designations GLARE-3 2/1 (t=0.85 mm), GLARE-4 2/1 (t=0.98 mm) and GLARE-5 2/1 (t=1.11 mm). Also tested to provide baseline data was aluminum 2024-T3 (t=1.02 mm). Fig. 1 below shows schematically the lay-ups of each of the fibre metal laminate materials that were tested. Each panel was constructed in a 2/1 configuration with two layers of aluminum and a single group of prepreg layers. The prepreg layers are composed of unidirectional S2-glass with an epoxy matrix. Note that the GLARE-3 2/1 variant is not a symmetric lay-up.

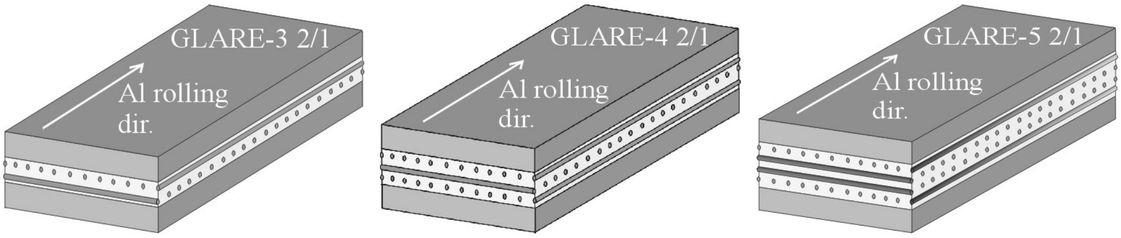


Fig. 1: Schematics of the variants of GLARE tested. The rolling direction of the aluminum sheet is defined as the $0^o$ direction.

*Instrumented Drop Weight Impact Tower and Development of the Clamping Fixture*

In order to qualify the equipment and to determine the energy levels for the formal test a series of preliminary impact tests were carried out on GLARE-3 2/1. Based on the results of these tests a new impact fixture was developed for the formal portion of the program. All panels were tested using an Instron-Dynatup instrumented drop weight impact tower shown in Fig. 2.

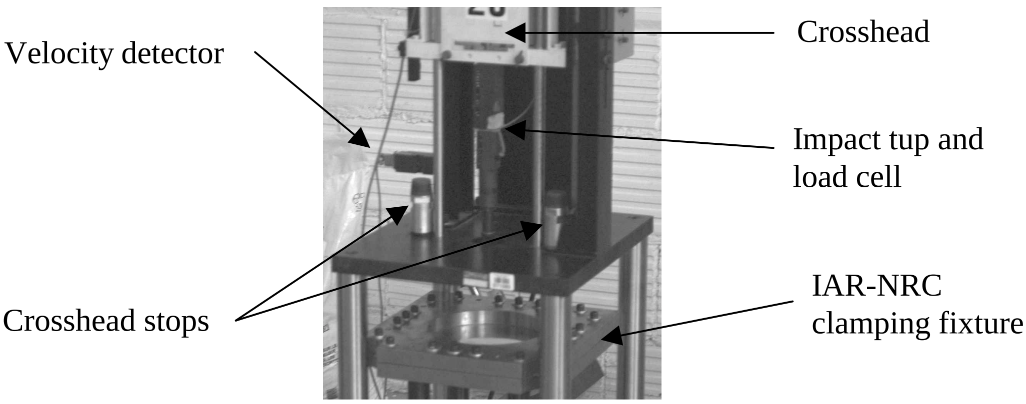


Fig. 2: Instron-Dynatup drop-weight impact tower, and clamping fixture.

An initial study was carried out using a NASA composite impact test fixture [1]. This fixture employed 267 X 178 mm (10.5 X 7 in) coupons with a 127 mm (5 in) square opening. Since the specimen had a long and a short axis, a symmetrical boundary condition did not exist. The effect of this is most evident when GLARE-3 was tested to puncture. Two specimens impacted at the same energy level, showed markedly different damage patterns as in Fig. 3. This result shows the effect of the fixture and of the differing lay-up of the two panels.

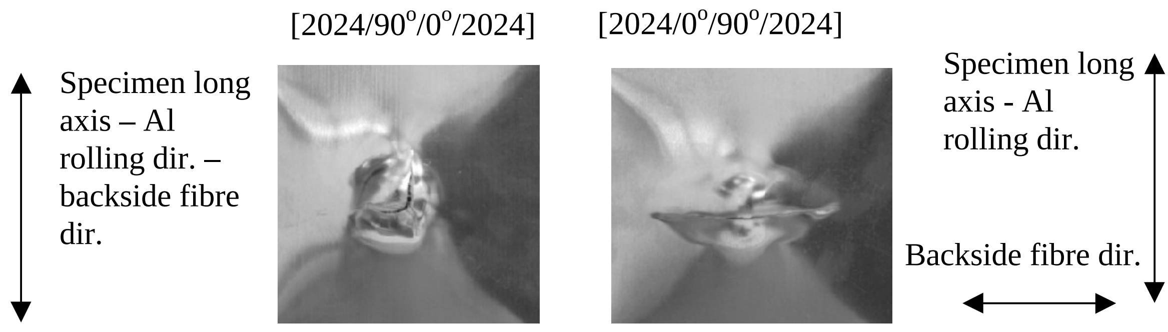


Fig. 3: Photographs showing the effect of lay-up and boundary for GLARE-3 panels impacted using the NASA fixture. $E_{imp}$ = 46 J (33.5 ft-lb.)

A new clamping fixture was thus developed, as shown in Fig. 4, to reduce the effects of the boundary conditions and to allow for the testing of large panels. Fig. 5 shows the effect of the fixture on the damage pattern observed in GLARE-3. The damage patterns are now the same except for a 90$^o$ rotation, as would be expected.

The test specimens were machined to a dimension of 292 X 292 mm (11.5 X 11.5 in). A circular opening with a diameter of 203 mm (8 in) was used to better represent the typical stringer spacing found in transport aircraft. The test specimens were clamped in the fixture using 28 bolts set to a torque of 10.2 N-m (90.0 in-lb.) to ensure consistent boundary conditions between specimens. The panels were then impacted with a 12.7 mm (0.5 in) diameter hemispherical steel indentor with a crosshead mass of 6.42 kg (14.2 lb.). The height of the crosshead was varied to provide the desired impact energy level to within +/- 2.5 J (1.9 ft-lb.).

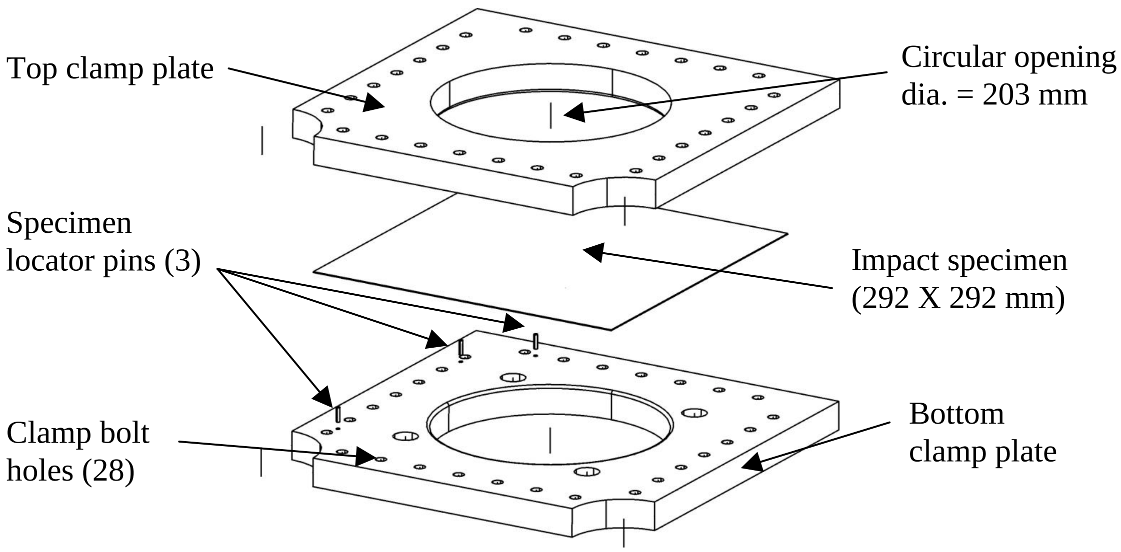


Fig. 4: IAR-NRC impact specimen clamping fixture, manufactured from mild steel.

Strain data was acquired using a 4-channel digital capture oscilloscope; the strain signals were amplified and conditioned using a standard bank of strain gauge amplifiers. A minimum of two gauges were applied to selected panels 38 mm (1.5 in) from the point of impact, one in the 0$^o$ degree direction and one in the 90$^o$ degree direction. Both uniaxial gauges pointed towards the impact point. Strain data was acquired to determine the peak strain experienced by the panel when tested. The strain differs greatly depending on the axis along which it was measured.  This provides information on the stress distribution in the specimens during impact.

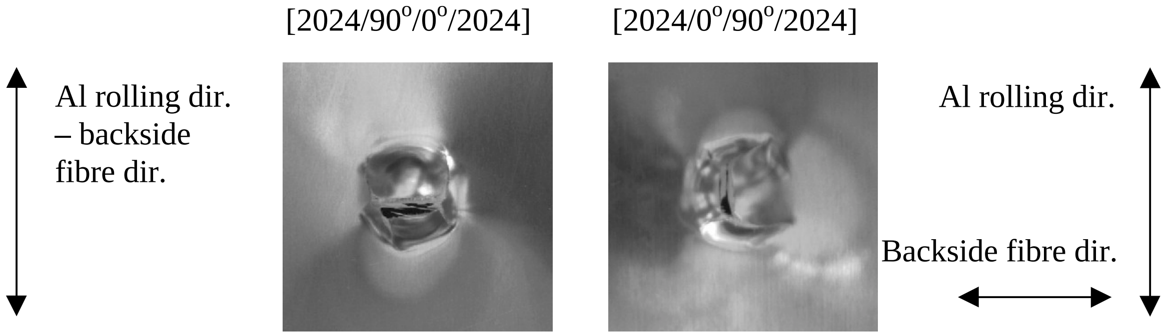


Fig. 5: Photographs showing the effect of lay-up and boundary conditions for GLARE-3 panels impacted using the IAR-NRC impact fixture.  $E_{imp}$ = 48 J (35 ft-lb.)

**Experimental Results**

The experimental results are presented in Table 1.  Each entry in the table represents the average of 2 to 5 individual panel values.  The results are displayed in terms of the areal density of the panels tested.

Table 1: Summary of impact test results normalized using the areal density of the specimens. The symbols are as follows: $E_{imp}$ – impact energy, $E_{abs}$ – absorbed energy, $F_{max}$, maximum impact force, and $\%E_{abs}$ – percent of impact energy absorbed.

| | $E_{imp}$ | Dent Depth | $E_{abs}$ | $F_{max}$ | $\%E_{abs}$ |
|---|---|---|---|---|---|
| | J | $mm/(kg/mm^2)$ | $J/(kg/mm^2)$ | $kN/(kg/mm^2)$ | % |
| 2024-T3 Aluminum | 26 | 2.3 | 6.7 | 2.0 | 73 |
| | 36 | 2.7 | 9.7 | 2.5 | 75 |
| | 46 | 3.2 | 13.3 | 2.8 | 81 |
| | 58 | 3.3 | 16.5 | 3.2 | 81 |
| | 62 | 3.6 | 18.1 | 3.4 | 82 |
| GLARE-3 | 16 | 2.9 | 4.7 | 1.9 | 63 |
| | 26 | 3.4 | 8.1 | 2.5 | 69 |
| | 37 | 3.9 | 11.9 | 3.2 | 71 |
| | 48 | 4.2 | 18.6 | 3.7 | 85 |
| | 52 | 4.4 | 24.2 | 3.7 | 102 |
| | 57 | 7.8 | 24.6 | 3.9 | 100 |
| GLARE-4 | 27 | 2.6 | 7.2 | 5.7 | 65 |
| | 37 | 3.1 | 10.3 | 7.1 | 67 |
| | 47 | 3.9 | 15.4 | 8.2 | 79 |
| | 53 | 4.2 | 19.6 | 8.6 | 80 |
| | 61 | 4.6 | 23.0 | 8.8 | 91 |
| GLARE-5 | 25 | 2.0 | 6.0 | 2.1 | 65 |
| | 34 | 2.4 | 8.3 | 2.6 | 65 |
| | 43 | 2.8 | 10.6 | 3.0 | 67 |
| | 47 | 3.1 | 12.4 | 3.3 | 71 |
| | 49 | 3.1 | 12.5 | 3.6 | 68 |
| | 57 | 3.5 | 15.9 | 3.9 | 75 |
| | 66 | 5.3 | 24.9 | 3.9 | 101 |

*Absorbed Energy*

Fig. 6 shows the absorbed portion of the impact energy, with respect to the level of impact energy. The value of absorbed energy has been normalized against areal density (density per unit area) for each of the materials tested. It can be seen from this plot that for a given impact energy level, the FMLs typically absorb a smaller fraction of the impact energy and thus return more of it to the impactor. When presented in terms of specific energy absorbed (Fig. 7) it can be seen that GLARE-5 2/1 performs the best. This lay-up has been optimized for impact resistance [2]. Each of the points on the graph is the average of between two and five samples. GLARE-3 punctures completely at an average of 47 J (34 ft-lb.). GLARE-5 exhibited complete puncture at an average energy level of 58 J (42 ft-lb.). Panels of GLARE-4 first exhibit cracking at approximately 49 J (36 ft-lb.). When GLARE-3 and GLARE-5 fail, all of the impact energy is absorbed so that there is no rebound of the impactor. GLARE-4 does not absorb all of the impact energy when it is partially punctured, some energy is still returned to the impactor.

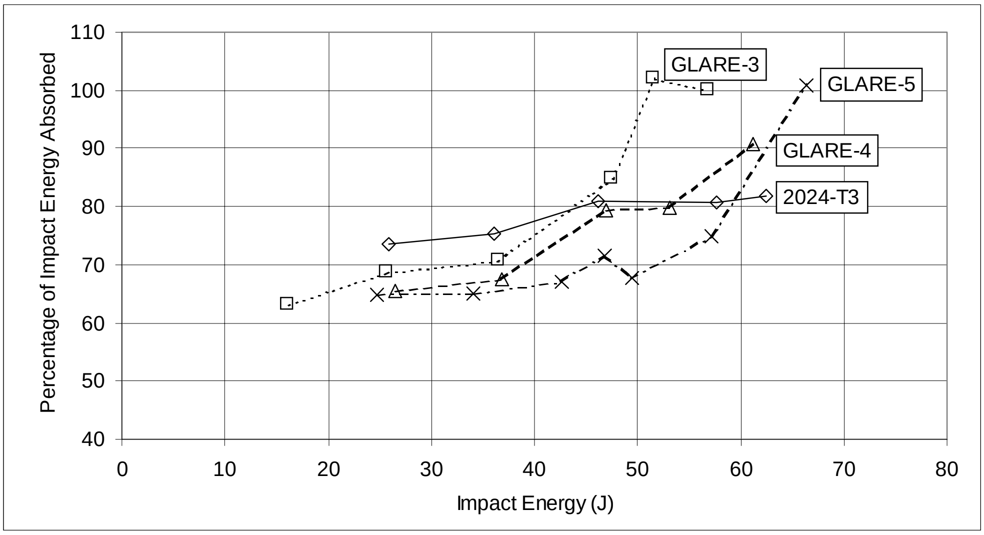


Fig. 6: Percentage of energy absorbed versus impact energy for GLARE© and 2024-T3.

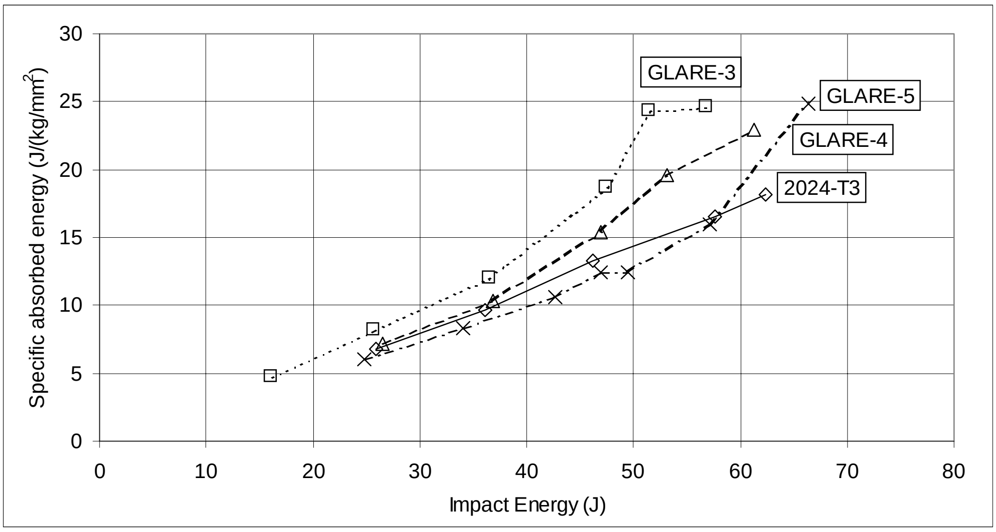


Fig. 7: Specific energy absorbed versus impact energy for GLARE© and 2024-T3.

*Dent Depth*

A common measure of the residual damage in FML panels following low velocity impacts is the depth of the plastically deformed dent [3,4]. The dent depths for all of the specimens were measured and then normalized using the areal densities of the materials to arrive at the specific dent depth. The specific dent depth is presented below in Fig. 8 versus the impact energy. The dent depths of GLARE-3 and GLARE-5 rise sharply when puncture occurs. GLARE-4 does not exhibit the same sharp increase in dent depth since it does not puncture completely. None of the specimens of 2024-T3 tested failed by puncture.

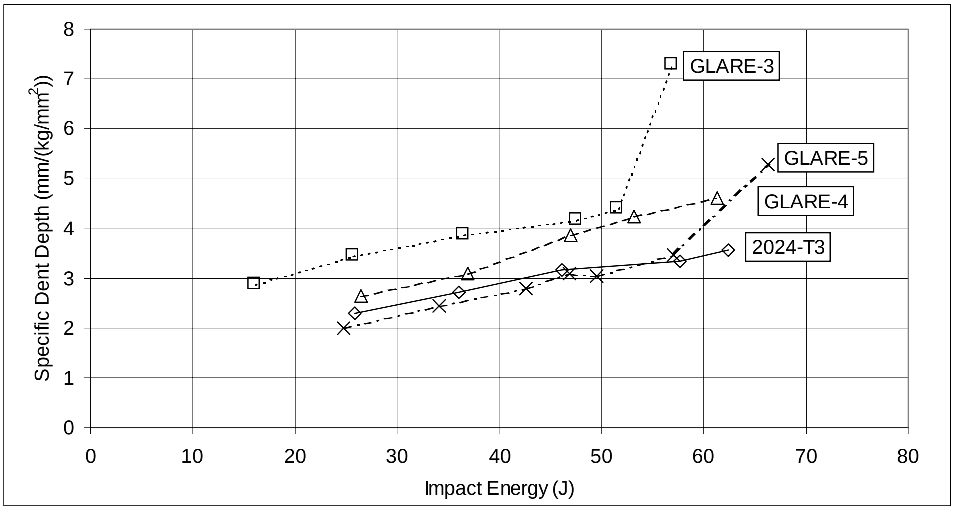


Fig. 8: Specific dent depth versus impact energy for GLARE© and 2024-T3.

*Impact Loads and Strains*

In Fig. 9 the typical load and strain traces for a GLARE-4 2/1 test panel are presented. The inset photograph shows the damage on the back-face of the panel. The crack is oriented in the rolling direction of the aluminum and the major fibre direction of the GLARE-4 panel, with the lay-up [2024/0°/90°/0°/2024]. This is typical behaviour for all GLARE-4 panels tested. The load curve shows the growth of the crack as a jagged plateau following the first load drop-off. Panels of GLARE-3 and GLARE-5 did not exhibit the same behaviour. They failed in an almost identical manner to each other. The load immediately drops off to almost zero once puncture has occurred.

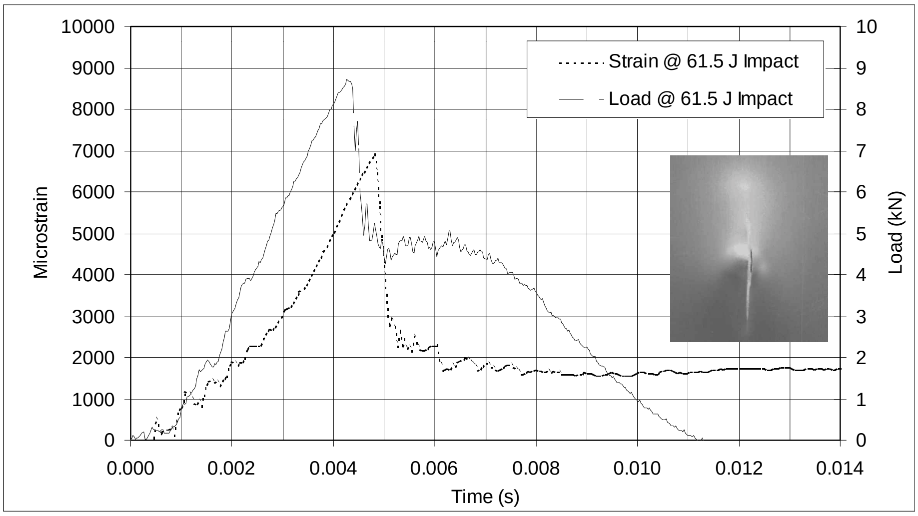


Fig. 9: Impact load and strain for a GLARE-4 2/1 panel impacted at an energy of 61.5 J.

It has been observed in GLARE-4 that as the impact load is increased beyond first failure the crack merely grows in length. For GLARE-3 and –5 increasing impact energies result in more severe puncture damage in the form of a larger hole in the panel. Also, cracks around the puncture in GLARE-3 and –5 occur in both the $0^o$ and the $90^o$ directions simultaneously. However, with GLARE-4 the single crack is always in the $0^o$ direction. This result indicates that GLARE-4 would be the material of choice for structures with primarily uniaxial loading conditions. The crack formed following impact should be parallel to the loading direction and would therefore not significantly reduce the strength of the panel. The unpredictable cracks formed in GLARE-3 and GLARE-5 would most likely significantly reduce the residual strength of the panel. In Fig. 10 the length of the crack observed in GLARE-4 2/1 panels is plotted versus impact energy. The crack length increases approximately linearly with increasing impact energy, with cracks first appearing around 48 J (35 ft-lb.).

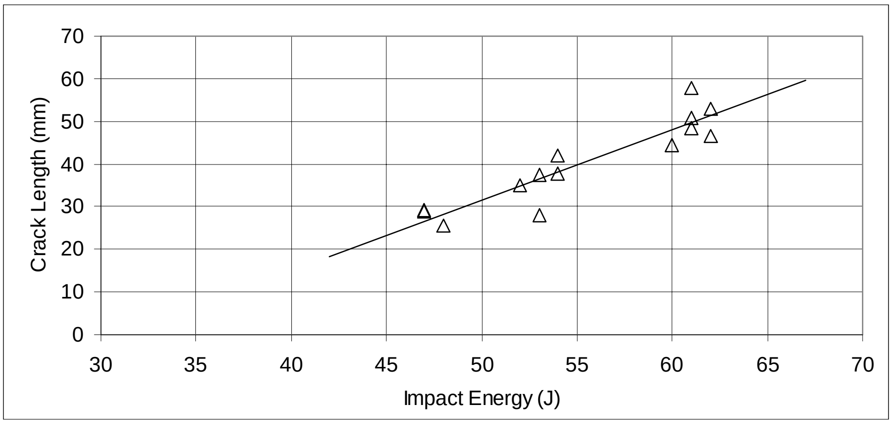


Fig. 10: Crack length for GLARE-4 2/1 impacted specimens.

*Internal Damage Characterization*

A novel enhanced x-ray technique developed by the NDI Group of IAR-NRC was employed to determine the extent of the internal damage following the impact tests. This allows viewing of the damage without complete destruction of the panels. It was found by this laboratory, and also reported by others, that ultrasonic C-scan could not be employed with FMLs due to the plastically deformed dent. Several of these X-rays are presented in Fig. 11 with the approximate associated impact energy levels.

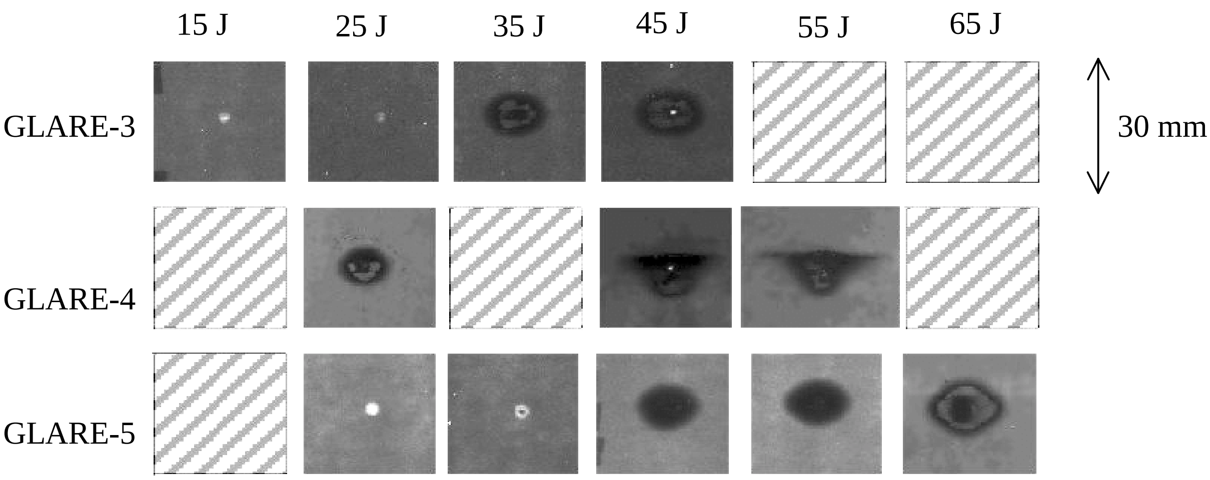


Fig. 11: Internal damage present in several variants of GLARE©.

## Discussion and Interpretation of Experimental Results

The preliminary impact tests conducted on GLARE-3 2/1 using the NASA impact fixture demonstrated that impact damage formation depends heavily on both the impact test setup and lay-up. Although the GLARE-3 specimens were quite thin, the relative position of the two unidirectional plies had a significant effect on the damage pattern when the panels were clamped in an unsymmetrical fashion. The clamping fixture developed at IAR-NRC created a symmetrical boundary condition. Tests with this fixture showed that it was the combination of lay-up and boundary condition that created the different damage pattern in GLARE-3 2/1. Impact test configurations should represent as closely as possible the boundary conditions to be found in the structural application that the material is intended for. Thus it is recommended that future work would involve examining the effect of impact with specimens under biaxial loading conditions representative of those experienced in actual airframe structures.

In terms of relative percentage of energy absorbed all of the GLARE specimens absorbed a smaller portion of the impact energy than aluminum 2024-T3. However, for the specific energy absorbed only GLARE-5 2/1 absorbed a smaller absolute amount than aluminum. This variant of GLARE© was developed by the manufacturer to be used in applications where there is significant risk of impact damage. The other variants of GLARE were optimized primarily for strength and fatigue crack growth resistance.

As described earlier GLARE-4 2/1 exhibits a predictable impact damage pattern, a single crack projecting parallel to the major fibre direction. It should be noted that the crack formed in GLARE-4 2/1 is very similar to that formed in GLARE-3 2/1 when tested in the NASA fixture. However, the mechanisms for the formation of the cracks differ widely. The NASA fixture has an asymmetric clamping condition that creates a higher stiffness in one direction. When the back-face fibres are oriented perpendicular (or parallel to the short axis of the panel) to the major stiffness axis they are unable to contribute effectively to the impact resistance. This allows the crack to grow parallel to these fibres, or perpendicular to the major stiffness direction. In GLARE-4 2/1 the crack grows perpendicular to the major stiffness axis or along the major fibre axis. It should also be noted that GLARE-1 and GLARE-2, in which all the fibres are oriented in the $0^o$ direction, would also behave in this manner.

## Estimation of Internal Damage Formation

There are four major forms of energy dissipation for FMLs subjected to low-velocity impacts. The various absorption routes are shown schematically in Fig. 12. First is plastic deformation (I) of the panel, the aluminum layers absorb most of the energy at this stage. Next delamination initiates (II), energy is then absorbed by a combination of plastic deformation and delamination formation. Some matrix cracking also occurs at this stage. In the third stage matrix and fibre damage (III) also begin to absorb a significant portion of the impact energy. Finally, puncture (IV) occurs and all of the energy of impact is absorbed. When GLARE-3 and GLARE-5 puncture, one hundred percent of the energy is absorbed. GLARE-4 will exhibit partial cracking as opposed to full through puncture, and thus one hundred percent of the energy will not be absorbed at low velocities. In contrast, fibre reinforced polymeric composites exhibit very little plastic deformation when impacted. Impact damage is primarily manifested in the form of matrix and fibre cracking and through extensive delamination.

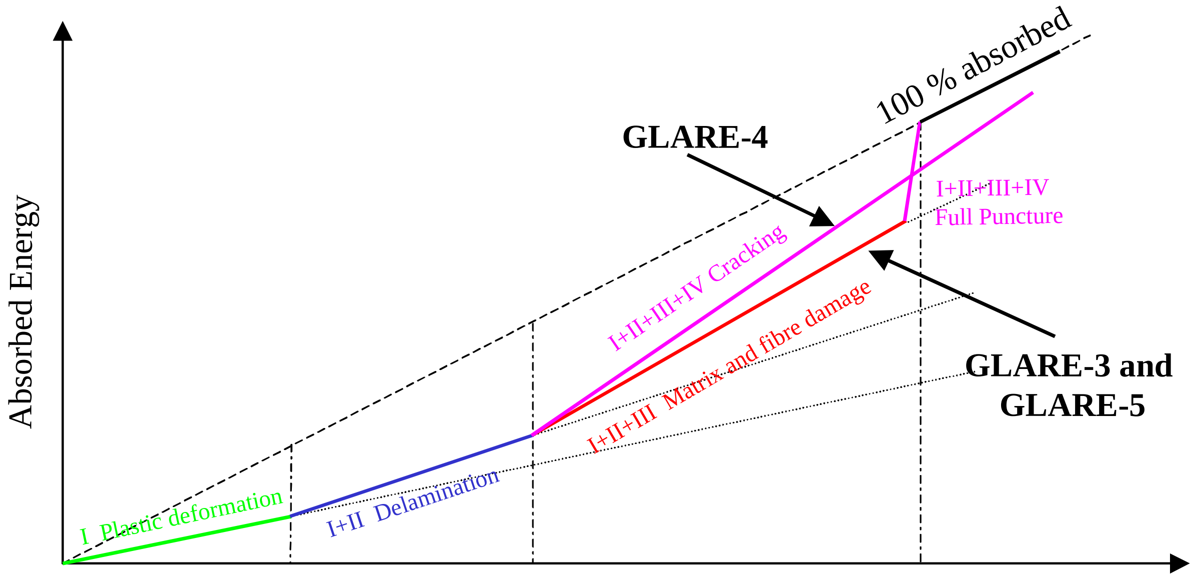


Fig. 12: Damage modes through which impact energy may be absorbed.

At energy levels much higher than required for puncture the percentage of energy absorbed drops. This occurs because the impactor passes completely through the panel and retains some of its kinetic energy instead of transferring it all to the panel or recovering it through rebound.

The x-rays in Fig. 11 clearly show the progression of the various damage modes. The dark regions seen in the 45 J and 55 J photographs for GLARE-5 are delamination-only regions. In the 65 J photo the lighter areas represent regions of significant fibre and matrix damage. The elongated dark regions in the GLARE-4 photographs are the unidirectional thickness-through cracks that formed as a result of the impacts.

In order estimate the amount of energy absorbed during impact and thus the relative amounts of damage formed it is necessary to determine the strain energy release rates of each of the damage modes. This requires further work examining each of the modes independently to determine their relative contributions.

## CONCLUSIONS AND RECOMMENDATIONS

The following conclusions can be made following these tests:

- Boundary conditions contribute significantly to the damage patterns observed in GLARE impact tests.
- The lay-up of panels has a significant effect on the resulting damage patterns.
- The symmetrical boundary condition and the size of the unsupported impact area provided by the IAR-NRC fixture eliminate damage modes not associated with the panel itself.
- GLARE-5 2/1 performs better than GLARE-3, GLARE-4 and 2024-T3 under low velocity, sub-puncture impact conditions. The internal damage formed allows for good dissipation of impact energy. First puncture of the GLARE-5 panels also occurs at a higher specific energy level than for either of the other two GLARE variants.

- GLARE-4 2/1 exhibits a predictable impact damage pattern that is favourable for use in fuselage applications. The crack formed following impact is oriented parallel to the major fibre direction which is also the major load axis, therefore the crack would not grow appreciably under applied loads.
- The crack in GLARE-4 grows proportionally with the impact energy while the damage in GLARE-3 and GLARE-5 does not change appreciably in size once the panel is penetrated.

Follow-on work should consist of:

- Impact tests conducted with specimens under uniaxial and biaxial loads.
- Residual strength post-impact tests measuring tensile, compressive and residual fatigue strengths.
- Development of a strain energy release model for estimating the damage formed in FMLs as a result of low velocity impacts.
- Component level impact tests on stiffened panels constructed of GLARE© FMLs.

## ACKNOWLEDGEMENTS

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