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Effect of impact damage on fatigue performance of structures reinforced with GLARE bonded crack retarders

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Abstract

Fibre-Metal Laminates (FML) such as GLARE are of interest as bonded crack retarders (BCR) to improve the fatigue performance of aircraft structures. The degradation of the performance of the crack retarder in service if subjected to damage is a critical factor in designing with this concept. Bonded assemblies of an aluminium alloy substrate reinforced with a GLARE strap were prepared, and were subjected to low velocity impact damage onto the GLARE, with impact energies ranging from 10 to 60 J. The thermal residual stresses developed during the bonding process of the GLARE to the aluminium were determined using neutron diffraction, and the change in the thermal residual stresses owing to impact damage onto the GLARE was evaluated. Pre- and post-impact fatigue

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performance of the BCR assemblies has been investigated. The results show that the BCR provides an improvement in fatigue life, but the reduction is impaired following impact damage. The results show that monitoring of impact damage will be critical in the damage tolerance assurance for aerospace structures containing bonded crack retarders.

Keywords: Bonded crack retarders, Fatigue crack growth, Impact fatigue, Residual stresses

1. Introduction

The use of large integral sections can significantly reduce the weight of an aircraft structure. However, integral structures show reduced performance with respect to damage tolerance because of a lack of physical barriers that can arrest a growing crack, such as exist in conventional structures joined with rivets and bolts. Aircraft structures in service experience a spectrum of loading which, in combination with the relatively high stress values attained can result in the development of fatigue cracks. For this reason, novel crack retarding features are being developed for aircraft structures that rely on integral construction [1,2].

As the technology has matured, advances in bonding techniques and the use of adhesively bonded composite patches as local reinforcement for repair and/or life extension of aircraft structures has proven effective. The principle is to adhesively bond a stiffening “strap” in regions where crack propagation can be expected. The local increase in stiffness owing to the strap will reduce the stress intensity factor at the crack tip, so reducing crack growth rates thereby resulting in longer life so allowing for longer inspection intervals [3,4]. GLARE is a promising fibre-metal laminate to improve damage tolerance by application as a bonded crack retarder [5]. It consists of alternating layers of thin aluminium sheet and glass-fibre-reinforced epoxy. GLARE combines low density and

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high strength with high damage tolerance and good resistance to fatigue cracking. Material properties such as impact, residual and blunt notch strengths, flame resistance and corrosion resistance are found to be significantly superior to those of monolithic aluminium alloys [6,7].

Using GLARE as a bonded crack retarder results in improved performance of the structure under cyclic loading. The glass-fibre epoxy layers provide high directional stiffness and high failure strains, which minimises structural failure even at high elastic strains. However a major concern over bonded crack retarder technology is the development of thermal residual stresses during the strap bonding process which arise owing to mismatch in the coefficient of thermal expansion between the GLARE and metal substrate. The main problem with thermal residual stresses generated in bonding to the aluminium substrate is that the tensile nature of the stresses induced in the aluminium substrate may have a negative impact on crack initiation and crack propagation behaviour thereby reducing the fatigue life improvement effects during service [8,9]. This can be particularly true for aerospace structures where low temperatures experienced at altitude can increase the residual stress significantly over that seen at room temperature [10]. Extensive research performed by Liljedahl *et al.* [8, 10-12] showed that the GLARE strap bonding process resulted in low thermal residual stresses compared to titanium, GFRP (glass fibre reinforced polymer) and CFRP (carbon fibre reinforced polymer). Hence GLARE has been selected for further study as an optimum material for use as a crack retarder.

The residual stresses will affect the stress/strain state of the structure and can result in a significant shift in the stress intensity factor range for a growing fatigue crack. This shift in the stress intensity factor will vary through the thickness of the bonded structure,

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particularly if a strap is fixed on one side only [13,14]. Thermal residual stresses during the composite bonding process can be reduced by lowering the curing temperature of the adhesive, but lowering the curing temperature will result in longer processing cycles which increases production cost and also reduces the glass transition temperature of the adhesive [15], which then limits the maximum operating temperature. In addition to this, a single-sided strap application will result in in-plane deflection of the specimen which may affect the fatigue life and crack propagation behaviour [2].

In recent years much attention has been paid [7,16,17] to damage tolerance and impact resistance of fibre metal laminates. Bagnoli *et al.* [7] studied the response of aluminium/GLARE hybrid materials to impact and in-plane fatigue. The specimen was reinforced with a GLARE strap on one side and the impact was performed on the non-reinforced side. They concluded that the impact on the aluminium substrate resulted in significant damage at the GLARE/aluminium substrate interface resulting in a reduction in fatigue life. However the effect of impact damage on GLARE and the efficacy when used as a bonded crack retarder has not been examined previously. Therefore the primary objective of this paper is to investigate the fatigue performance of GLARE bonded to a 5-mm-thick aluminium substrate when subjected to low velocity impact damage. Impacts were made onto the GLARE, and residual stress measurements and fatigue tests were performed with and without impact damage. The conclusions from this research will provide key information to design engineers on the thermal residual stresses owing to GLARE bonded crack retarders and the effects of impact damage on the GLARE that will help in developing acceptance criteria in cases where bonded crack retarders are seen to suffer damage in-service.

2. Experimental procedure

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2.1. Materials

Single-edge-notched tension (SEN(T)) substrate specimens were prepared with dimensions $400 \times 140 \times 5$ mm^3. A notch of 17 mm was introduced in the SEN(T) specimens before bonding the strap. The substrate thickness is indicative of that in wing cover applications. GLARE 2A-6/5 was chosen as the crack retarder strap, which consists of six layers of aluminium alloy sheets (0.4 mm thick) and five double layers (0.26 mm thick) of unidirectional glass fibre-reinforced epoxy oriented along the longitudinal direction of the strap. The mechanical properties for GLARE 2 (6/5) are tensile modulus (E_1) = 64.1 GPa, ultimate tensile strength (σ_{ts1}) = 1091 MPa and tensile yield stress (σ_{y1}) =331 MPa and, compressive yield strength (σ_{cs1}) = 366.4 MPa. The dimensions of the strap were $200 \times 100 \times 3.7$ mm^3. The GLARE strap configuration was chosen to give the desired stiffness ratio in the test coupons [18]. The front edge of the strap was placed at 37 mm from the edge of the specimen and thus the distance between the front edge of the strap and the crack tip was 20 mm. The design of the specimens was chosen to optimize the current study for unambiguous identification of the effects of the impact damage on residual stresses in the substrate and fatigue performce of the bonded crack retarders. The assembly was bonded using FM94® adhesive supplied by Cytec Ltd. Prior to bonding, the surface of the substrate and the external aluminium sheets of GLARE were etched with Phosphoric Acid Anodizing (PAA) which involves alkaline degreasing followed by PAA and priming with BR 127, a modified epoxy phenolic primer with corrosion inhibiting properties [19, 20]. Table 1 shows the mechanical properties of Al substrate, FM94 and GLARE constituents used in this investigation. Figure 1 shows the geometrical details of the SEN(T) coupon specimens and impact damage residual stress measurement locations.

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Specimens were prepared at Cranfield University. The curing temperature was 120°C and the curing cycle was as follows.

- Apply vacuum at ambient temperature for a minimum of 15 minutes and increase the temperature at a rate of 3°C/min from ambient to 125 ± 5°C, and increase pressure in autoclave to 520 kPa.
- Vent vacuum when the pressure reached 415 kPa, or when the temperature reached 60°C, then apply a pressure of 520 kPa at 125°C for 90 minutes.
- After 90 minutes, turn off theheat and allow to cool to below 60°C, whilst maintaining thepressure, prior to removing the samples from theautoclave.

After cure the specimens were inspected using an ultrasonic phased array to confirm the bond quality. The direction along the longest dimension is hereafter referred to as the longitudinal direction (X), the direction along the width dimension is referred to as the transverse direction (Y), and the distance through the thickness is referred to as the normal direction (Z) as shown in figure 1.

2.2. Impact damage

Low velocity impact tests were performed at Cranfield University with an instrumented falling weight rig fitted with a second strike preventer. For impact, the specimens were clamped within a steel frame fitted with a rectangular aperture. A 20-mm-diameter hemispherical indenter was used and the total mass of the impactor was 2.54 kg. A series of impact energies ranging from 10-60 J were applied.The impact damage resistance was characterized by investigating the indentation depth and width of the damaged area using a laser co-ordinate measurement machine, which provides a three-dimensional morphology of the impact damage. For post-impact fatigue tests a total of five specimens were

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prepared, two specimens impacted with 20 J and three specimens impacted with 35 J energy.

2.3. Residual stress measurements

Neutron diffraction is an established non-destructive technique used to determine strains within metallic structures. Inter-planar distances of atomic lattice planes are determined from the positions of the diffraction peaks by using Bragg's law [21]. The measured strain in a particular direction can be computed if the inter-planar distance of an unstressed (reference) sample is available and is given by:

$$\varepsilon_{(x,y,z)} = \frac{d_{(x,y,z)} - d_0}{d_0} \qquad \text{Equation (1)}$$

Where ε represents strain, $d_{(x,\ y,\ z)}$ represents the inter-planar distance in the bonded sample and d_0 represents the value obtained for an unstressed sample.

Neutron diffraction measurements were performed using POLDI (Pulse-OverLap Diffractometer) [22] at the Paul Scherrer Institut (PSI), in Switzerland; and at SALSA (Strain Analyser for Large and Small scale engineering Applications) diffractometer [23] at the Institut Laue-Langevin, France. POLDI is a time of flight (TOF) diffractometer where multiple lattice plane reflections are measured at once. SALSA is a monochromatic strain diffractometer where single lattice reflections are measured. Aluminium is face-centred cubic and measurements were made using the {311} lattice plane as this has been found to give the best approximation to the macroscopic strain response [24]. The wavelength used at SALSA was 1.648 Å.

Measurements were carried out along the crack growth direction (Y-direction) from the notch tip, as shown in figure 1. Strains were measured in the three assumed principal directions: longitudinal, transverse, and normal. Measurements were performed in two

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specimens, one without impact damage to quantify the residual stresses developed during the bonding process. The second specimen was impacted in three different locations (figure 1), on the GLARE with three different energies of 20 J, 40 J, and 60 J to investigate the change in the stresses owing to impact damage.   The three impacts were made on a single specimen, with wide separation between them, in order to facilitate the subsequent residual stress measurements.The centre of the impact location was 90 mm from the edge of the specimen for both 20 J and 40 J impacts, and 86 mm for the 60 J impact. The slight variation in the impact location is a result of positioning difference of the specimen during impact. All residual stress measurements, except for the 20 J impact, were performed at two different thickness locations, at z =1.5 and 3.5 mm from the reinforced side in the aluminium plate. Owing to time constraints the region impacted with 20 J was measured only at z =1.5 mm.

The specimen without impact damage and the specimen impacted with 60 J were measured at POLDI. A gauge volume of 2 × 1.5 × 5 mm was used. The shortest dimension was always in the through-thickness direction to avoid averaging of the through-thickness stress, and the longest dimension was in the longitudinal direction to improve the counting statistics. The remaining measurements were carried out at SALSA with a 2 × 2 × 2 mm^3 gauge volume. After residual stress measurements the specimens with and without impact damage were subjected to constant amplitude fatigue crack growth testing.

2.4. Fatigue testing

All the constant amplitude fatigue crack growth tests were performed at room temperature using a 100 kN MTS servo hydraulic test machine. Specimens were subjected to a maximum stress of 60 MPa at 10 Hz and with a load ratio *R* of 0.1. The maximum stress

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and *R* ratio are representative of the levels that would be experienced in typical aerospace application and this is a reference design stress for the envisaged application. Crack length measurements were performed with a travelling microscope with an accuracy of ± 0.01 mm. Tests were performed according to ASTM standard E647. A total of 11 specimens were tested, three specimens without a strap, three specimens bonded with GLARE strap with no impact damage, two specimens bonded with GLARE strap and impacted with 20 J, and three specimens bonded with GLARE strap and impacted with 35 J.

3. Results and discussion

3.1. Impact behaviour

The impact resulted in visible damage on the GLARE strap in the form of plastic deformation. Figure 2 shows optical images of the impact damage on the GLARE and figure 3 shows results of laser co-ordinate measurement on the GLARE strap impacted with different impact energies ranging from 10 J to 60 J, and the impact damage morphology of a specimen impacted with 50 J. Table 2 summarizes the depth and width of damage resulting from the impacts on the GLARE.

3.2. Residual stress measurements

High temperature adhesive curing results in the development of thermal residual stresses, and specimen distortion arises owing to the asymmetric configuration with a strap on one side of the specimen only. The effects of impact on the residual stresses are of particular interest. Measurements were carried along the crack growth direction (Y-direction) from the notch tip. Data from a point well outside of the bonded area close to an edge were obtained in all three principal directions and were used to provide the stress-free values required in the computation of residual stresses. Figure 4 shows residual stresses in the aluminium plate at z =1.5 mm distance from the strap side.

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From figure 4 it can be seen that in the specimen without impact damage the thermal residual stresses developed during the strap bonding process are relatively low. Also the measurements remote from the impact location in the impacted specimens show low stresses: the apparent variation in the stresses remote from the impact locations may not be real since the magnitude of the measured stresses are very low and approach the sensitivity of the technique. Also, the hydrogen-containing adhesive present in the assembly causes incoherent scattering of the neutrons which impairs the signal-to-noise ratio. There is also likely to be more inherent scatter in the data from the SALSA instrument, where only a single diffraction peak is used which will be sensitive to changes in texture through the plate thickness. This is not the case for the measurements performed at POLDI, where Pawley refinement of many diffraction peaks was used which effectively removes any texture effects.

Measurements performed at z = 3.5 mm in the substrate are shown in figure 5 (owing to time constraints it was not possible to measure the specimen impacted with 20 J at this location). The results show a large variation in the stresses at and around the impact area compared to the specimen without impact damage. The impact damage at this depth shows the development of high compressive stresses in the longitudinal and transverse directions and low compressive stresses in the normal direction. The low compressive stresses in the normal direction are a result of the specimen not being constrained in this direction and owing to Poisson's contraction in this direction.

The specimen without impact damage shows very low stresses through the thickness which are almost constant along the width of the specimen. There is significant variation in the stresses developed owing to impact at different energies. Compressive residual stresses developed during impact increase with an increase in impact energy.

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Measurements performed at z = 1.5 mm show low stresses compared to measurements at z = 3.5 mm in both longitudinal and transverse directions. Stresses in the normal direction are always lower than the stresses in the longitudinal and transverse directions.

4. Fatigue tests

High-temperature adhesive curing and single-sided strap bonding processes result in specimen distortion owing to the asymmetric configuration. Prior to fatigue testing, the out-of-plane distortion of the specimens was measured using a laser co-ordinate measurement machine and the results are shown in figure 6. The distortion measurements were performed along the longitudinal direction on the unreinforced side. A total of two specimens were measured to obtain the baseline distortion and two specimens each at 20 J and 35 J impact. It can be seen from figure 6 that the impact damage on the GLARE results in a change to the specimen distortion. Impacting has overlaid a new distortion that acts in an opposite sense to that resulting from the high-temperature adhesive curing.

After impact damage analysis, fatigue tests on specimens with approximately 0.3 mm damage depth were conducted, representing the barely visible impact damage (BVID) scenario, which may be caused by tool drop. Figure 3b shows an example of the three dimensional impact damage morphology measurements performed by laser co-ordinate measurement on the specimen impacted with 50 J. For easy visualisation, a two dimensional impact damage line profile at the maximum impact damage depth was extracted from each impact and is shown in figure 3a. From table 2 and figure 3 an impact energy of 35 J, which produces 0.3 mm depth of damage on the GLARE, was selected as giving the required level of damage for fatigue testing. Three SEN(T) specimens (as shown in figure1) were prepared and impacted at 35 J on the GLARE. In addition, two further

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fatigue tests with specimens impacted at 20 J were conducted. Figure 7 shows the crack length versus number of cycles for each specimen.

Constant- amplitude fatigue crack growth tests on the SEN(T) coupons show that the specimens with a strap have a longer life compared to specimens without a strap, confirming the efficacy of the bonded crack retarder concept. The specimens with a strap produced a fatigue life more than double that of the fatigue life of an unstrapped specimen, and the life improvement factor for the strapped specimens was 2.26. Specimens impacted with 20 J and 35 J have shorter fatigue lives than the strapped specimen without impact damage, but had longer life when compared to an unstrapped specimen. Specimens impacted with 20 J showed a 16% reduction in fatigue life whereas the specimens impacted with 35 J showed a 55% reduction in fatigue life when compared to the undamaged strapped specimen.

The shorter fatigue life of the impact damaged specimens is attributed to the additional residual stresses and interfacial damage introduced at the bonding interface. There was no evidence of any damage within the strap as a result of the crack growth in the substrate. However, specimens impacted with 20 J and 35 J suffered interface damage in the form of delamination between the GLARE and the substrate and hence a lower fatigue life. The specimen impacted with 35 J exhibits a greater degree of interface damage, greater residual stresses after impact, and lower fatigue life when compared to the specimen impacted with 20 J.

Conclusions

Residual stresses associated with GLARE bonded crack retarders on an aluminium plate have been determined using neutron diffraction with and without impact damage applied to the GLARE. Fatigue lives of samples with and without a strap were measured, and the

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effect of impact damage on fatigue life was determined. From this research the following conclusions can be drawn.

1. The thermal residual stresses developed during the adhesive bonding process of GLARE at elevated temperature are very low, below 50 MPa.
2. Impact damage on the GLARE results in the development of a residual stress profile through the substrate thickness and around the damage location. There is significant variation in residual stress through the thickness of the aluminium plate, with lower stresses close to the bonded strap side and higher compressive stresses further from it. The peak compressive stresses were in excess of 200 MPa.
3. The inclusion of the bonded crack retarder strap results in fatigue life improvement. Impact damage on the GLARE results in lower fatigue life when compared to specimens without impact damage. There was a greater reduction in fatigue life as the impact energy was increased, with a 35 J impact giving a 55% decrease in fatigue life.
4. It can be concluded overall that the beneficial effects of bonded crack retarders are highly-susceptible to impact damage in-service, and that impact damage, even at the barely-visible threshold (BVID) level results in the generation of significant residual stresses. Even though the stresses are compressive below the impact site, the overall effect of the damage is to reduce the fatigue life.

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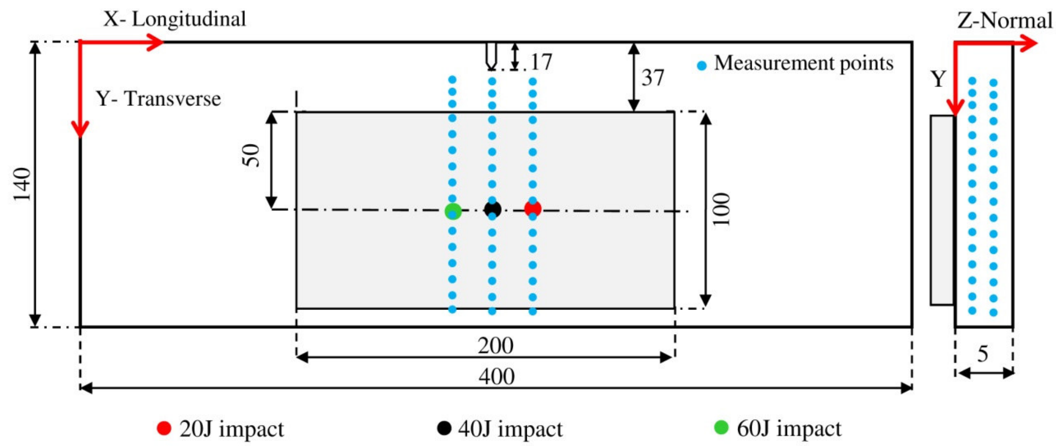

Figure 1. Geometrical details of the SEN(T) specimens

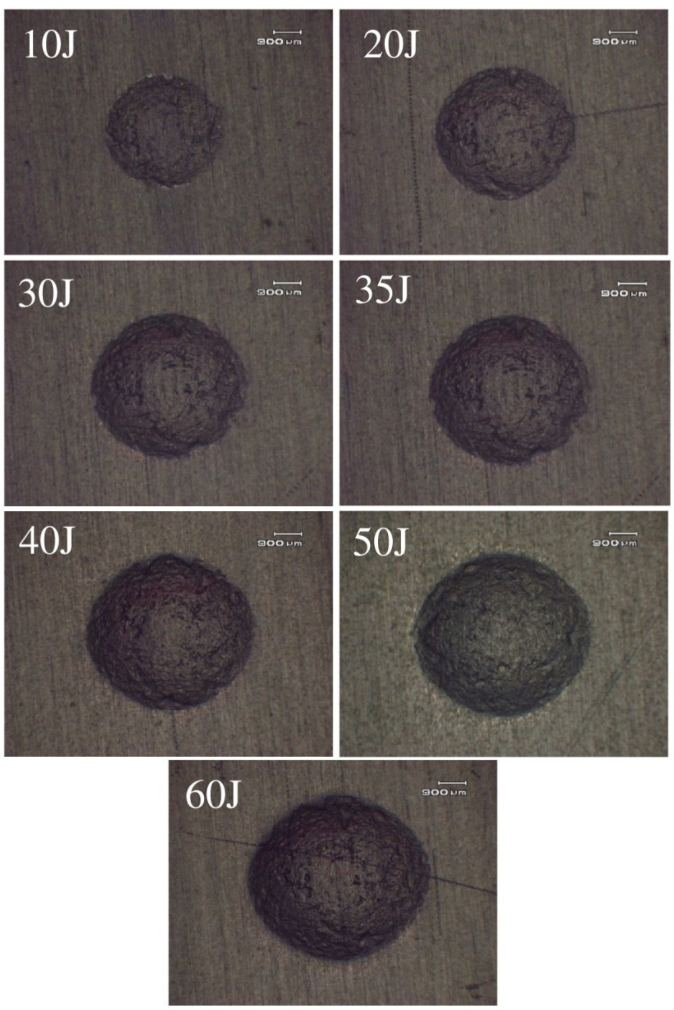

Figure 2. Optical images of impact damage on the GLARE, showing plastic deformation

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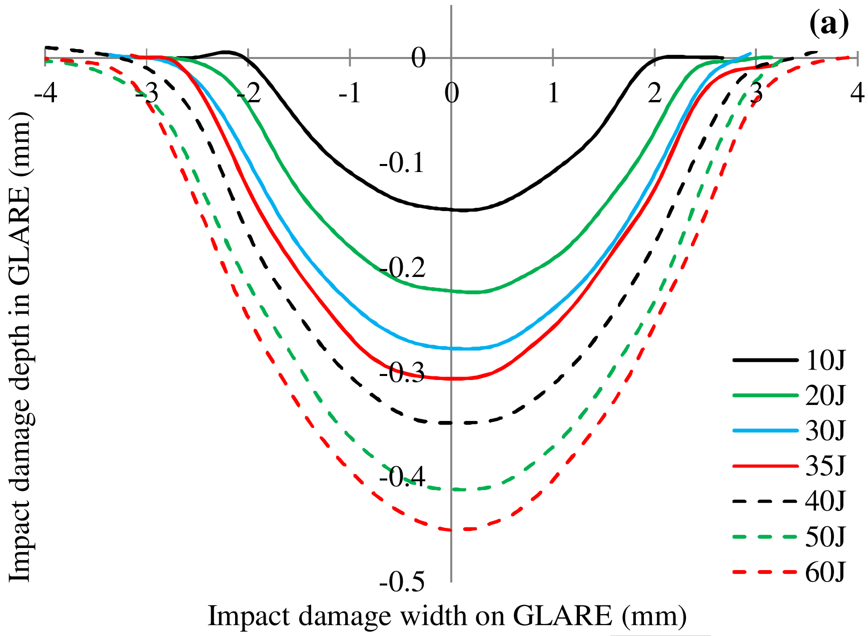


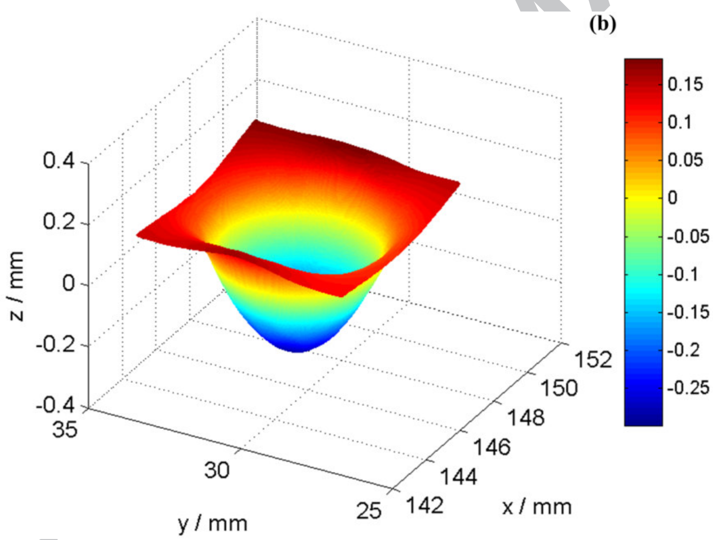
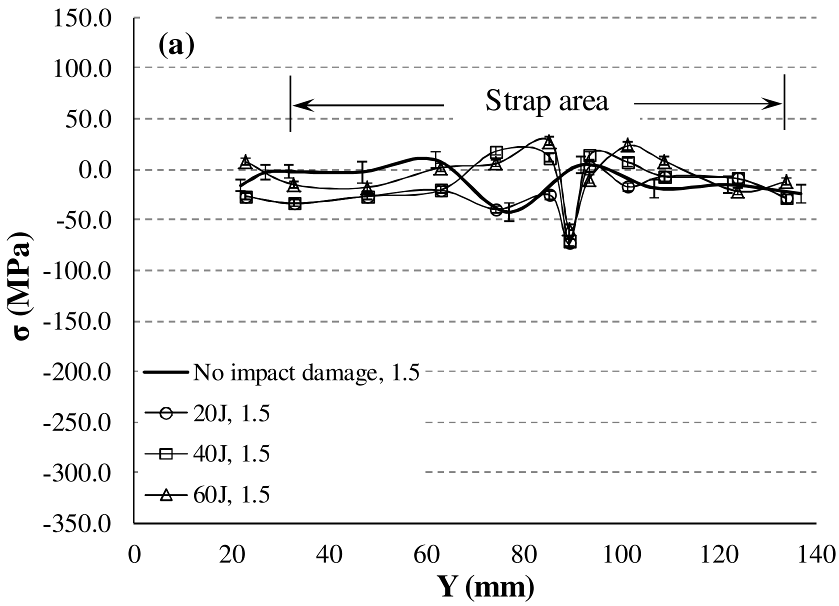
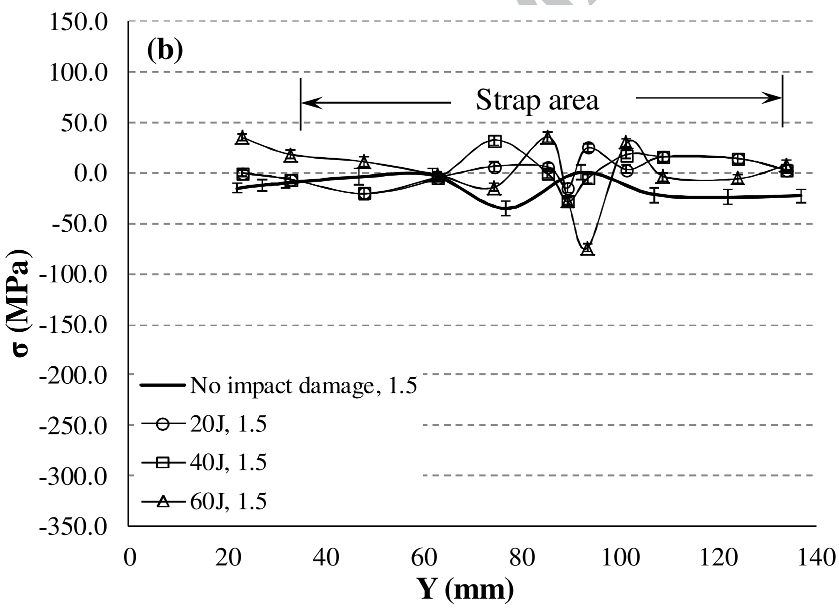


Figure 3. (a) Impact damage profiles determined by laser co-ordinate measurement (b) Impact damage morphology of the specimen impacted with 50 J





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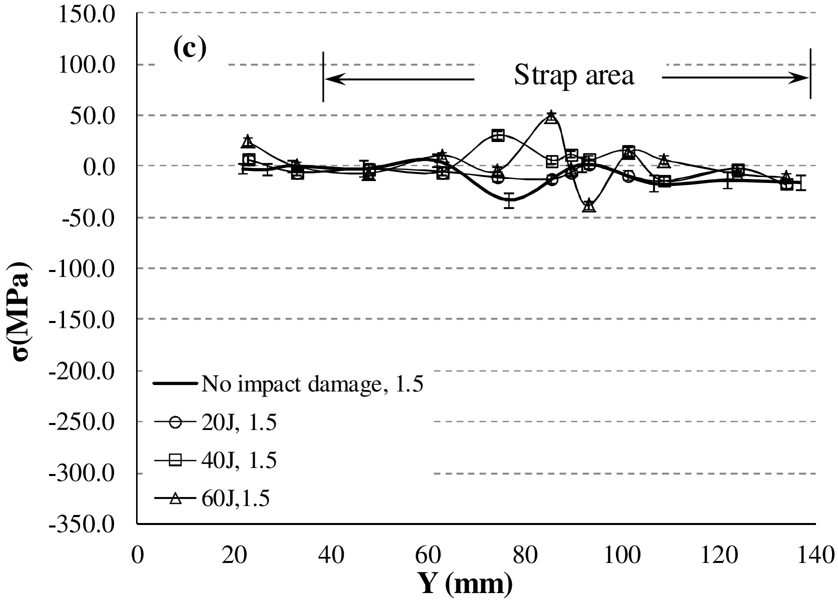
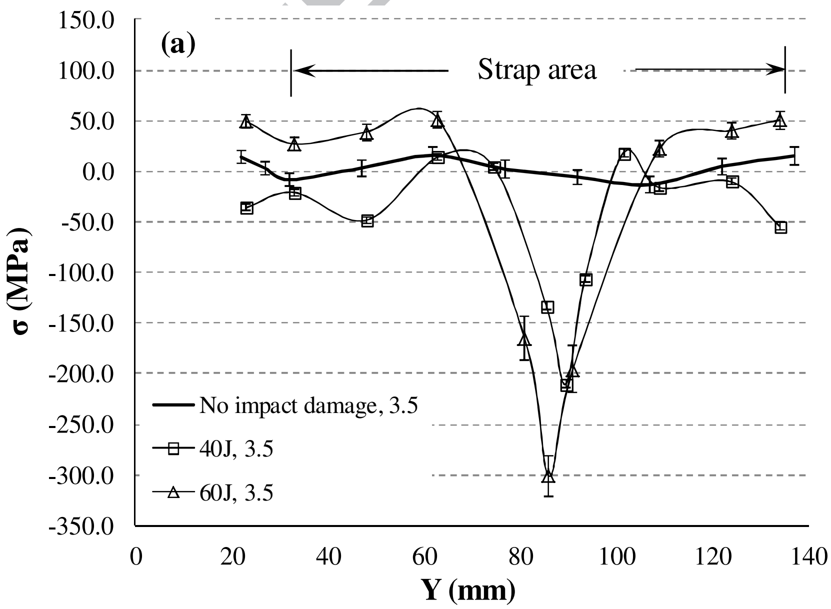


Figure 4. Residual stress in the aluminium plate at z = 1.5 mm from the reinforced side before and after impact damage (a) Longitudinal (b) Transverse and (c) Normal component of stress



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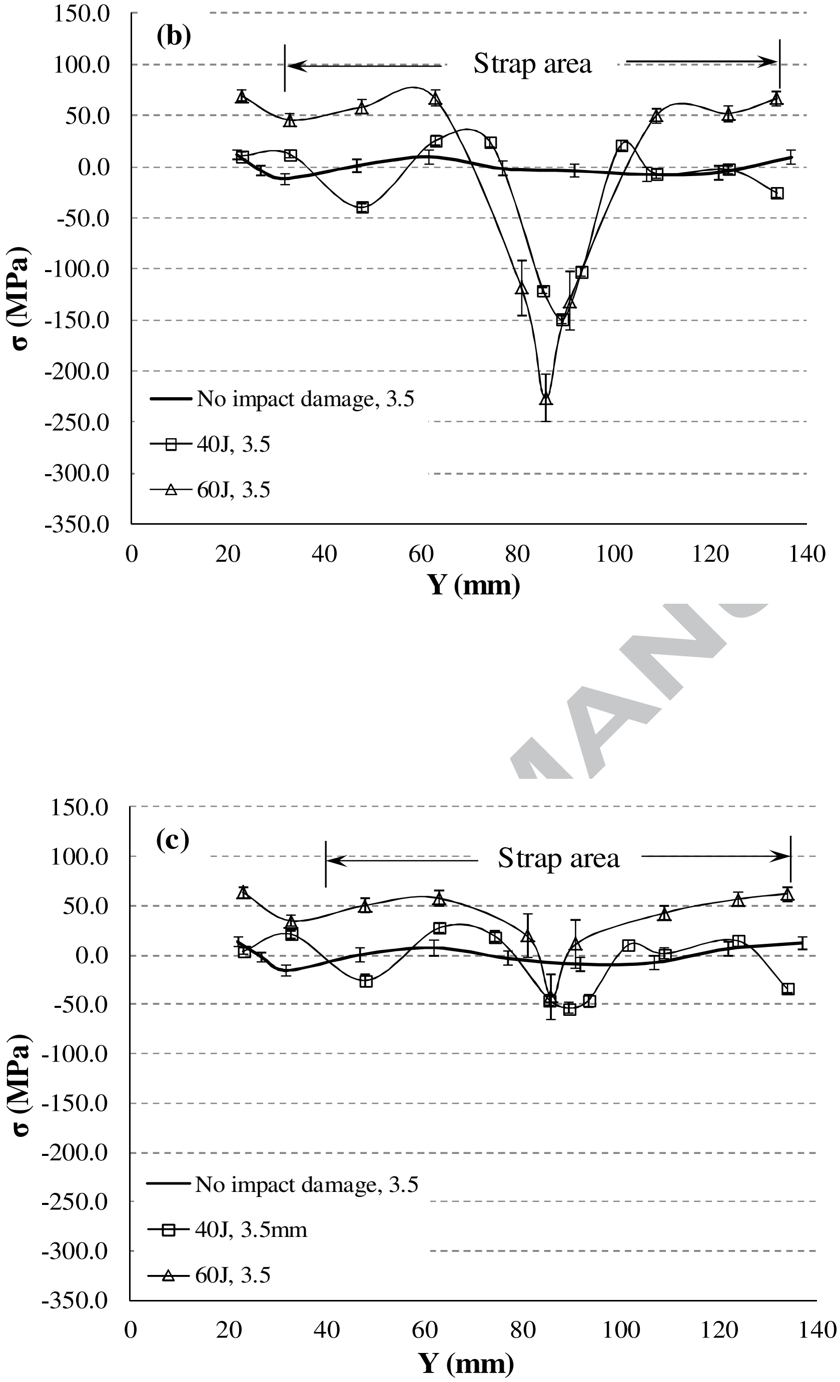

Figure 5. Residual stress in the aluminium plate at z=3.5mm from the reinforced side before and after impact damage (a) Longitudinal (b) Transverse and (c) Normal component of stress

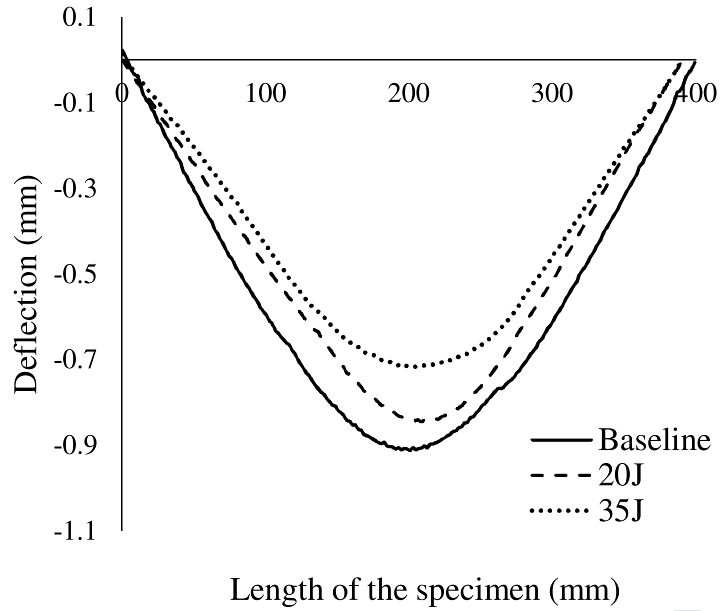

Figure 6. Distortion of the SEN(T) specimens in the longitudinal (x) direction before and after impact

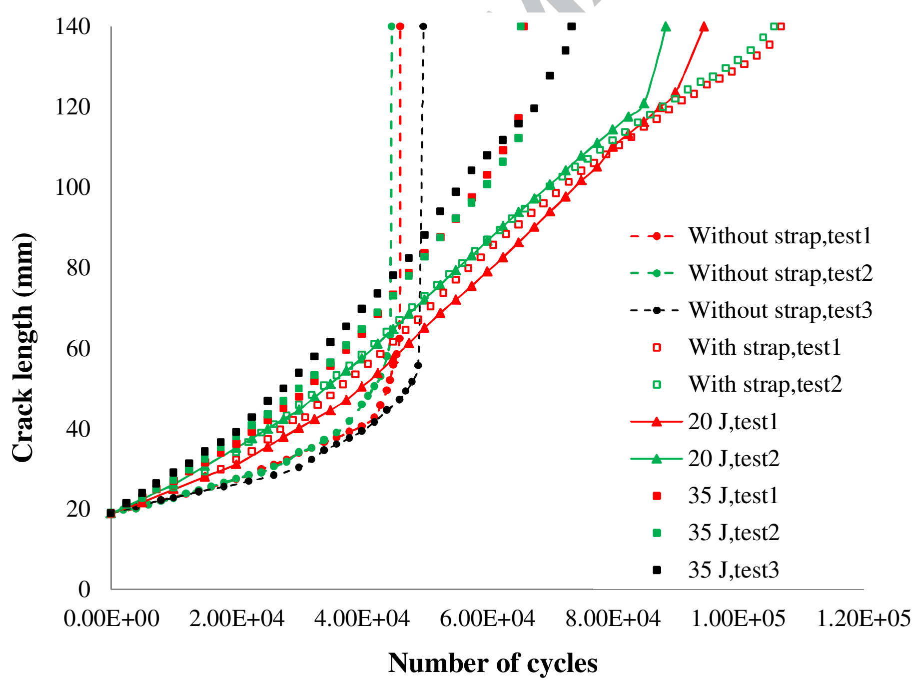

Figure 7. Fatigue tests on the SEN(T) coupon specimens

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Property	**Al 2624-T351**	**FM 94**	**GLARE constituents**	
			Al 2024-T3	**S2 glass-prepreg**
E_{11} / GPa	73	1.9	72	50.3
E_{22}, E_{33} / GPa	71	1.9	72	5.5
$\nu_{12} = \nu_{13}$	0.33	0.52	0.30	0.31
ν_{21}	0.33	0.52	0.30	0.03
CTE_{11} / 10^{-6}°C^{-1}	23.2	58	23.2	2.88
CTE_{22} / 10^{-6} °C^{-1}	23.2	58	23.2	40.3

Table 1: Mechanical properties of materials used in this project

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Impact energy/J	10	20	30	35	40	50	60
Damage depth/mm	0.14	0.22	0.27	0.31	0.35	0.41	0.45
Damage width/mm	4	5.2	5.6	6	6.4	7.04	7.52

Table 2. Post impact damage analysis

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Highlights

- Thermal residual stresses owing to bonding GLARE bonded crack retarders are low.
- Impact damage at 30 J or above resulted in visible plastic deformationon GLARE.
- Impact damage depth is proportional to impact energy.
- Application of bonded crack retarder resulted in improved fatigue performance.
- Specimens with impact damage showed lower fatigue life than undamaged specimens.

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