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An experimental study of low velocity impact response in 2/2 twill weave composite laminates manufactured by a novel fabrication process

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Abstract A novel fabrication process for advanced composite components—the Quicktep^{TM} process was described. 2/2 twill weave MTM56/CF0300 carbon epoxy composite laminates were manufactured by the Quickstep and the autoclave processes. The response of these laminates to drop-weight low velocity impact at energy levels ranging from 5 to 30 J was investigated. It was found that the laminates fabricated by the Quickstep had better impact damage tolerance than those fabricated by the autoclave. Optical microscopy revealed extensive matrix fracture in the center of the backside of the autoclave laminates indicating the more brittle property of the epoxy matrix cured by the autoclave process. Interfacial shear strength (IFSS) for two composite systems were measured by micro–debond experiments. The MTM56/CF0300 material cured by the Quickstep showed stronger fibre matrix adhesion. Since the thickness and density of the impact targets produced by two processes were different, finite element analysis (FEA) was performed to study the effect of these factors on the impact response. The simulation results showed that the difference in thickness and density affects the stress distribution under impact loading. Higher thickness and lower density caused by processing lead to less endurance to drop weight impact loading. Therefore the better performance of Quickstep laminates under impact loading was not due to the thickness and density change, but resulted from stronger mechanical properties.

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Introduction

Quickstep^{TM} is a novel fabrication process using a fluid filled, balanced pressure and heated floating mould technology for producing advanced composite components. It was invented in Western Australia and has been supported by Australia's Commonwealth Scientific & Industrial Research Organization (CSIRO) and Victorian Centre for Advanced Materials Manufacturing (VCAMM). It works by suspending a rigid mould between an upper and lower bladder which contains heat transfer fluid circulating in a low pressure environment. Quickstep provides a much faster cure cycle than the autoclave process due to the fact that liquid can be heated or cooled much faster than gas as a heat transfer medium. Composite laminates are very susceptible to impact damage during fabrication, handling and services. Low velocity impacts such as a tool drop, gravel impacts can produce the barely visible impact damage (BVID) which dissipates the incident energy by a combination of matrix damage, fibre fracture and fibre matrix debonding [1–3]. Drop weight impact tests were performed to assess the MTM56/CF0300 woven carbon epoxy laminates fabricated by the Quickstep and the autoclave processes. The internal damage of the quasi-isotropic laminates was investigated by the dye penetrant X-radiography technique and optical microscopy.

Interfacial adhesion is one of the crucial properties affecting the strength and life of composite materials. The micro–debond technique has its advantage over fibre pull-out and single fibre fragmentation methods by being capable of measuring the interfacial shear strength (IFSS) in situ thus allowing investigation of a composite in its post processed form [4]. The IFSS for two composite systems were obtained by the shear lag analysis.

Finite element analysis (FEA) has been shown to be a powerful tool to simulate and analyze composite structures under the impact loading [5–7]. The Quickstep and the autoclave processes produce laminates with different thickness and density. The effect of the thickness and density of the impact target on the response to impact loading should be considered when the impact tolerance of two systems are compared. ABAQUS 6.4 software was utilized for simulating the drop weight impact event.

Quickstep fabrication method

Quickstep was invented to reduce costs for aircraft quality parts production where the autoclave process is widely employed. It utilizes an industrial heat transfer fluid (such as polyalkylene glycol) transferring heat to the composite part which is trapped between a free floating rigid (or semi-rigid) mould. Flexible membranes are bonded into pressure chambers creating the upper and lower halves of the mould set. The mould is floating in a balanced low pressure environment within the heat transfer fluid without distortion or stress. Due to the fact that liquid contains thousands of times the heat energy per volume of gas, the heat transfer rate for liquid is much higher than that for gas. High ramp rates can be realized for heating and cooling by the Quickstep process which greatly reduces the processing time. Very fast ramp rates can normally cause dangerous exothermic reactions; however, Quickstep has the capacity to remove the heat generated by reactions by transferring it into a massive heat sink—heat transfer fluid. Therefore the exothermic reaction is effectively controlled. A vibrator on top of the pressure chamber can disperse air bubbles and minimize the residual stresses by vibrating the heat transfer fluid inside the chamber. The illustration of the working process is shown in Fig. 1 [8].

Experimental

Material processing

MTM56/CF0300 2/2 twill weave carbon epoxy prepregs were purchased from the Advanced Composites Group. Composite laminates were manufactured using the American Autoclave ''mini-bonder'' MB-2036-415-315-800 at the Australian National University and the Quickstep QS5 at Deakin University. Pre-pregs were cut into sheets, laid up to $[45/0/-45/90]_{2s}$ quasi-isotropic laminates and vacuum bagged as shown in Fig. 2. Solid release film and breather were laid on top of the laminate under the vacuum bag. Fibre glass tape was stuck along the edges of the laminate to stop the resin flow during curing.

The autoclave and Quickstep cures applied to the MTM56/CF0300 composite are shown in Fig. 3. The solid lines represent the parameters for the autoclave cure and the dotted lines represent the parameters for the Quickstep cure. Both of the two types of materials were cured at 120 °C for 10 min. The autoclave cure cycle was chosen according to the manufacturer's recommendations from the material data sheet of ACG MTM56. 620 κPa nitrogen pressure was employed during autoclave processing. The Quickstep cure utilized the fast ramp rate of heat transfer fluid of this process. –97.47 to –97.76 κPa vacuum was achieved when the cure was performed. The Quickstep cure consumed 77% less time than the autoclave cure and applied relatively low nitrogen pressure (7–28 κPa) which reduced energy consumption.

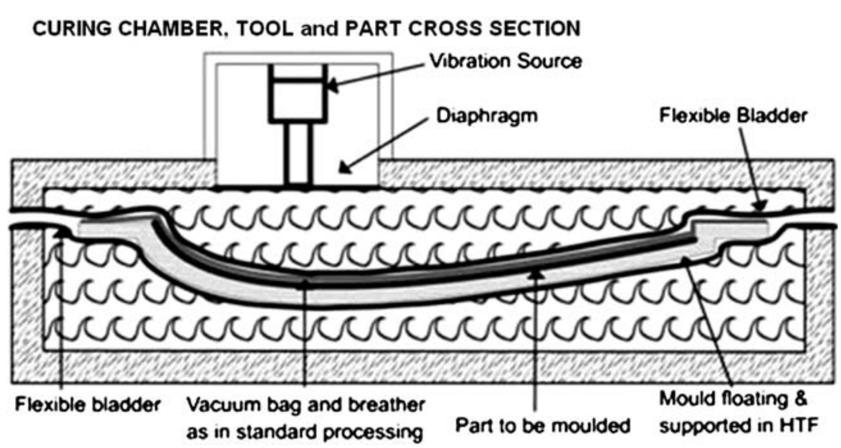

Fig. 1 The principle of working process for Quickstep [8]

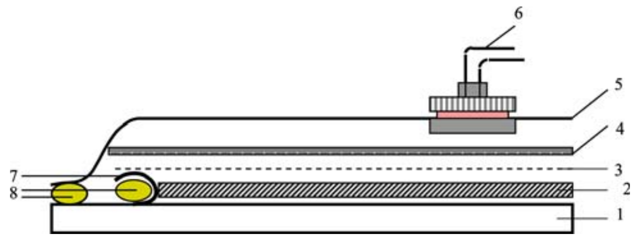

Fig. 2 Vacuum bag assembly for Quickstep and autoclave processes. (1) aluminum plate; (2) laminate; (3) solid release film; (4) breather; (5) vacuum bag; (6) vacuum line; (7) fibre glass; (8) sealant tape

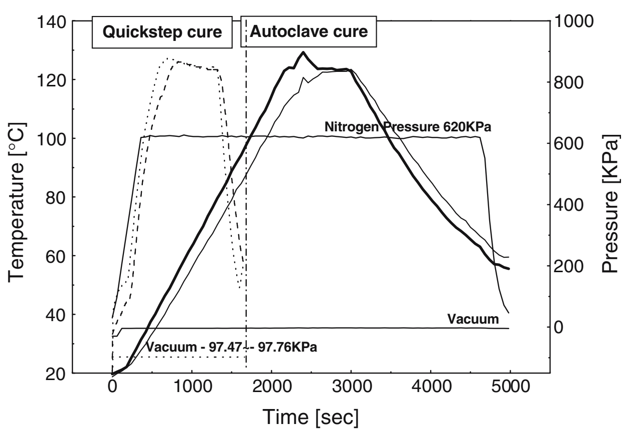

Fig. 3 Cure cycles for MTM56/CF0300 composite by using autoclave and Quickstep processes. The autoclave cure: 89 κPa/min pressure build-up; 3 °C/min heat-up; 10 min hold at 120 °C; 2 °C/min cool-down; 102 κPa/min pressure release; The Quickstep cure: On average 9 °C/min heat-up; 10 min hold at 120 °C; 12 °C/min cool-down; constant vacuum –97 κPa. Two temperature profiles were obtained from two thermal couples respectively

Experimental procedure

After the panels were cured, they were cut into $150 \times 100\ \text{mm}^2$ coupons. Impact tests were performed with a drop weight BMT CLASS I impact tester which was built according to the Boeing Specification Support Standard 7260 at CSIRO (Clayton). Five impact energy levels were applied to coupons which were 5, 11, 17, 24 and 30 J. The impact damage was examined by means of the dye penetrant (a zinc iodide solution was used) enhanced X-radiography and optical microscopy.

The laminates were cut and mounted into standard metallographic specimens for micro–debond tests. Specimens were finely polished before debond tests were performed using the Ultra-Micro Indentation System (UMIS) II. The Berkovich diamond tip was utilized for nanoindentation in the centre of fibres. Each indentation test consisted of loading a given fibre to a predetermined load. Then the fibre was unloaded and the specimen was inspected by the Dual Scope^{TM} DS45-40 Atomic Force Microscope (AFM) to detect any debonding. The maximum load was increased from 30 mN in 10 mN increments until debonding was observed.

Numerical simulation

In this study, the drop weight impact behaviour was estimated with the finite element method using ABAQUS 6.4 software. The voids and other defects during fabrication were ignored. The fibre misalignment and the effect of the hygrothermal strain from curing were also neglected. Each coupon was supported against translations at the outer periphery and was impacted by a hemispherical impactor with a prescribed initial velocity. The radius of the impactor was 7.94 mm and the mass was 5.48 kg. The impactor was positioned to strike normally at the center of the target plate. The model mesh was composed of 4660 elements and 4882 nodes. S4 R elements were used for target simulation and R3D4 elements were used for impactor simulation. The four edges of the target had boundary conditions applied to constrain all six degrees of freedom so that the target does not move. Rotation of the impactor was constrained as well. The general contact algorithm of ABAQUS was used to define the contact between the impactor surface and the target surface. It makes use of the all-inclusive, element-based surface that is defined automatically by ABAQUS/Explicit.

The mechanical property data inputted to the models can be found in Table 1. The elastic moduli were obtained from experimental data and the Poisson ratio was taken from Ref. [9]. The geometry and physical data for laminates manufactured by two processes are summerised in Table 2. The laminate manufactured by the autoclave was represented by LA and laminate fabricated by the Quickstep was represented by LQ. The finite element model used here is presented for an elastic target plate, where damage was suppressed and the potential for damage was analyzed.

Results and discussions

Damage assessment of laminates impacted at low velocity ranging from 1.35 to 3.30 m/s.

X-ray images (Fig. 4) were taken after the laminates were impacted at energy levels 5, 11, 17, 24 and 30 J corresponding to initial impact velocities 1.35, 2.00,

Table 1 Elastic mechanical data of woven MTM56/CF0300 for numerical simulation

Material	E_1 (GPa)	E_2 (GPa)	ν_{12}	G_{12} (GPa)	G_{13} (GPa)	G_{23} (GPa)
Woven MTM56/CF0300	17.7	15.5	0.36	9.2	9.2	9.2

Table 2 Geometry and physical data for MTM56/CF0300 composite laminates manufactured by autoclave and Quickstep processes

Impact Specimen	Length (mm)	Width (mm)	Thickness (mm)	Density (kg/m^3)
LA	152	102	3.856	1480
LQ	–	–	4.016	1427

2.49, 2.96 and 3.31 m/s. Visible indentation was present with laminates impacted at energy levels 17, 24 and 30 J which showed evidence of plastic deformation. Surface damage on the backside of laminates was only found from specimens impacted at 30 J. By comparison, the LQ showed less damage than the LA. Parameters for damage area were measured from the indentation region and X-ray images which are recorded in Table 3. As the impact energy increased, the impact damage became more severe. The residual indentation of the impact side for the LQ had a bigger diameter but a smaller depth. The measured diameter of damage region from X-ray images is 2.77 mm less for the LQ than the LA at energy level 17 J and is 4.82 mm less at energy level 30 J.

In this investigation, the opaque dye (zinc iodide solution) was utilized to infiltrate the damaged areas before irradiation of the coupon. The limitation of this method is that the internal damage not connected to the surface cannot be impregnated with the solution so it remains undetected. Optical micrographs were taken cross the section along the center line to reveal the internal damage. The microstructure of laminates impacted at energy 17, 24 and 30 J is shown in Fig. 5.

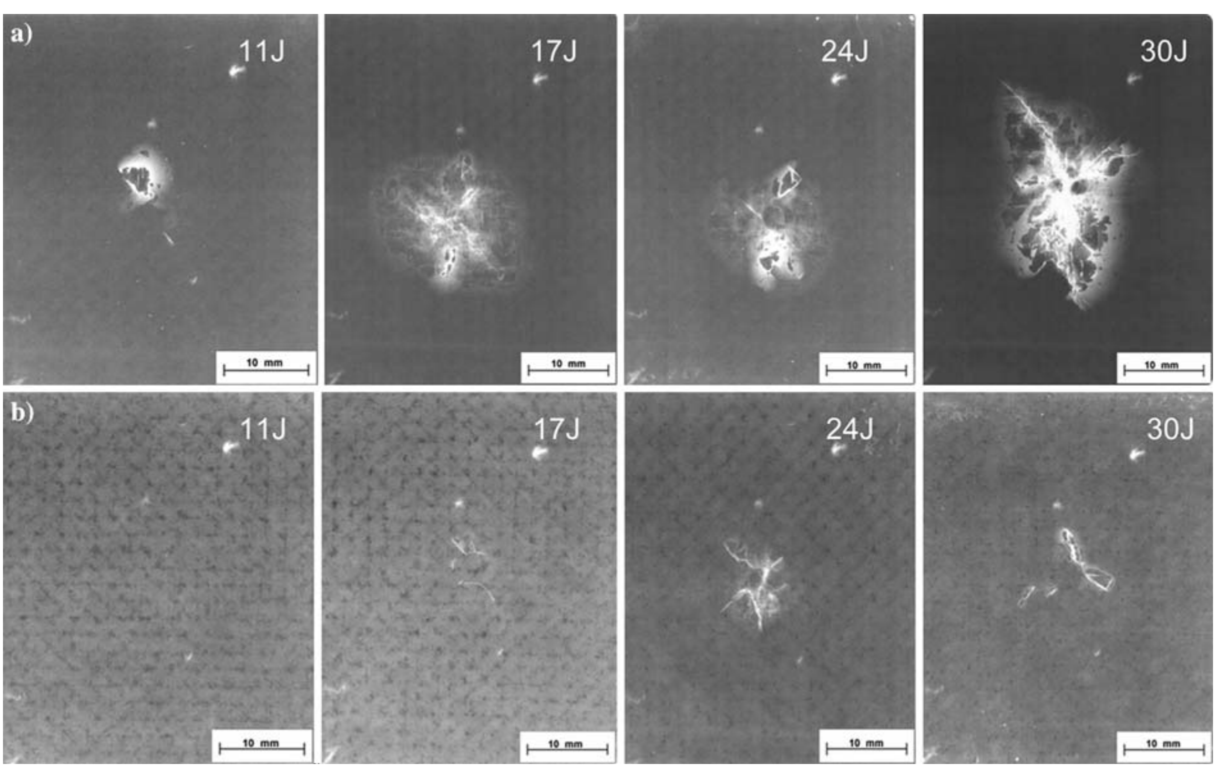

Fig. 4 X-ray damage detection of MTM56/CF0300 woven laminates as a function of impact energy: (a) laminates manufactured by autoclave; (b) laminates manufactured by Quickstep. Impact was performed at energy levels 5, 11, 17, 24 and 30 J. No damage was detected at impact energy 5 J. The white dot on the top right corner was from the X-ray source

Table 3 Measurements of impact damage for MTM56/CF0300 laminates manufactured by autoclave and Quickstep processes

Impact specimen	Impact energy (J)	Diameter of residual indentation (mm)	Depth of residual indentation (mm)	Diameter of damage area (mm)
LA	17	4.05	0.08	12.34
	24	3.91	0.12	11.44
	30	3.94	0.17	16.89
LQ	17	4.39	0.07	9.57
	24	4.29	0.12	10.19
	30	4.25	0.14	12.07

The main failure modes of fibre reinforced polymer laminates under impact are matrix cracking, delamination, fibre breakage, fibre buckling and penetration [1, 10]. All the above failure modes were found from the microstructure except penetration due to the low impact energy level. At low velocities, flexible targets respond to impact loading primarily by bending which generates high tensile stresses in the lowest ply [11]. This causes the matrix cracks in the lowest ply. However, the low velocity impact damage for stiff targets is initiated by high contact stresses on the impact side. By comparing the microstructures of two systems, we find that the LA exhibited severe matrix failure in the lowest ply (as illustrated in Fig. 5) despite that the LQ presented different microstructure without extensive matrix cracks in the lowest ply. From the failure mode of the laminates, it is believed that the LQ was stiffer than the LA under low velocity impact loading.

Matrix properties play a dominant role in determining the damage threshold and extent. Avmerich et al. [12] believe that brittle composites tend to

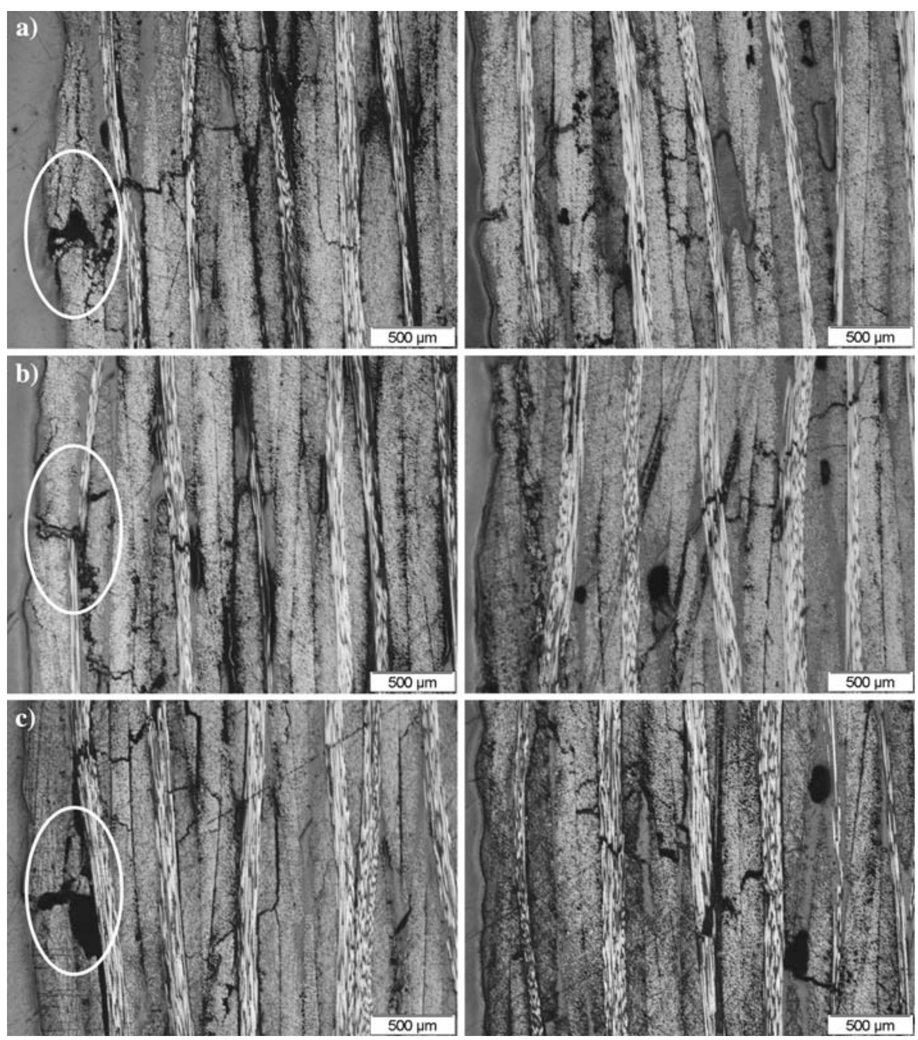

Fig. 5 Micrography of impact damage for laminates fabricated by autoclave and Quickstep. The impact direction was from the right to the left. The ellipse illustrates the damage of the centre in the lowest ply: (a) the LA and the LQ impacted at energy 17 J; (b) the LA and the LQ impacted at energy 24 J; (c) the LA and the LQ impacted at energy 30 J

dissipate a large amount of energy by matrix fracture. Soutis et al. [13] concluded from their work that materials with more ductile resins suffer less impact damage. The fact that the LA exhibited extensive matrix fractures indicated a more brittle property of the matrix within this material. Impact failure including matrix fracture was restrained by the higher strain capability of the matrix of LQ. This agrees with authors' recent research [14] that HexPly914 composite system cured by Quickstep had more ductile matrix than that cured by autoclave and had better fibre wetting hence increased the mode I interlaminar fracture toughness.

Interfacial adhesion measurements

The micro–debond experiment results are shown in Table 4. The IFSS was calculated using the shear lag analytical approach which was used by Desaegar and Verpoest [15]:

$$\tau_{\text{debond}} = \frac{nF_{\text{debond}}}{2\,\pi\, r^2}$$

$$n = \frac{2E_{\text{m}}}{E_{\text{f}}(1+v_{\text{m}})\ln(\frac{2\,\pi}{\sqrt{3}}V_{\text{f}})}$$

τ_{debond} is the interfacial shear strength, F_{debond} is the measured debond load, r is the fibre radius, E_{m} is the matrix modulus, E_{f} is the fibre modulus, v_{m} is the matrix Poisson's ratio and V_{f} is the local fibre volume fraction. The IFSS was higher for the LQ than the LA indicating stronger fibre matrix adhesion of the MTM56/CF0300 cured by the Quickstep process.

Numerical results and discussions

Figure 6 presents the computed contact force vs. time plot of the impact event. The mechanical data inputted to the models are shown in Table 2. The model using the thickness and density of the autoclave-cured material is represented by model-A and that using the thickness and density of the Quickstep-cured material is represented by model-Q. At 5 J impact energy, the threshold force value was 4.9 KN for model-A and 5.3 KN for model-Q. Davies and Robinson [16, 17] predicted the threshold force based on an isotropic axisymmetric analysis using the mode II strain energy release rate,

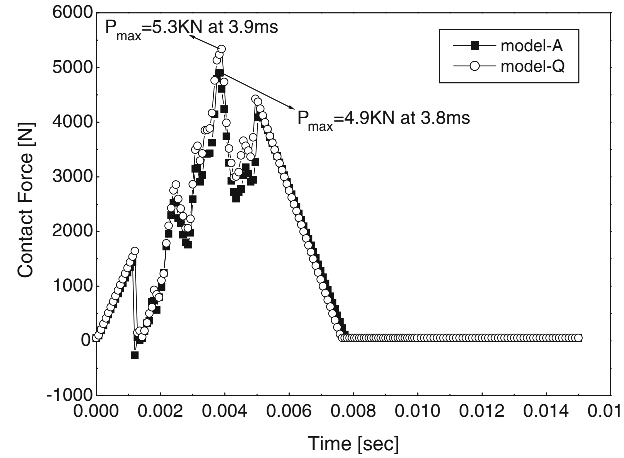

Fig. 6 Computed force/time history for composite laminates under impact loading at 5 J energy level

$$P_{\text{c}}^2 = \frac{8\,\pi^{\,2}Eh^3G_{\text{IIC}}}{9(1-\upsilon^2)}$$

where P_{c} is the threshold load, G_{IIC} is the mode II critical strain energy release rate, E is the Young's modulus, h is the thickness of the plate and v is Poisson's ratio. Their prediction agrees well with their experimental data on quasi-isotropic laminates. The G_{IIC} value for MTM56/CF0300 was tested to be 2200 J/m^2 by end notched flexure test. So the threshold load of this impact event was calculated to be within the range of 4.7–5 KN according to this equation. The simulation results for the threshold load values fit reasonably to the expected result.

Figures 7 and 8 show the stress distribution for the impact sides of the model-A and the model-Q impacted at 30 J energy level respectively. At 0.75 and 1.5 ms, the stress magnitude was comparable for both laminates. However, when time reached 2.25 ms, the stress on the center of the model-Q increased 563–742 MPa which was higher than that on the center of the model-A, 539–563 MPa. The higher stress magnitude on the center of the model-Q target causes impact damage more easily. Consequently, the better performance of laminates cured by the Quickstep process under impact loading was not caused by thickness and

Table 4 Input data and results of interfacial shear strength (IFSS) calculation

Material	E_{m} (GPa)*	E_{f} (GPa)*	v_{m}*	V_{f} (%)	IFSS (MPa)	Std. deviation (MPa)
LA	3.7	234	0.41	55.56	33.72	3.03
LQ	3.7	234	0.41	54.73	37.47	3.11

* Reported by authors from reference[14]

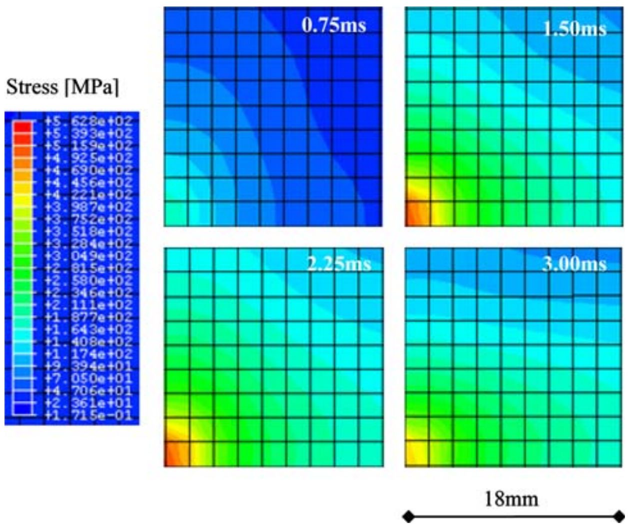

Fig.7 Stress distribution for the impact side of the quasi-isotropic laminate manufactured by the autoclave process impacted at 30 J energy level

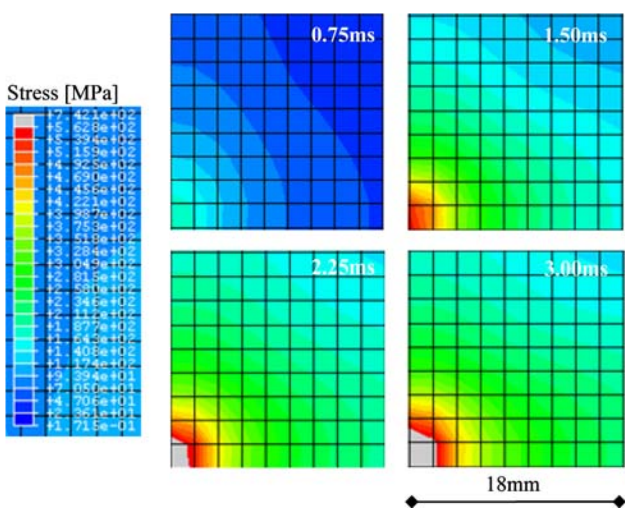

Fig. 8 Stress distribution for the impact side of the quasi-isotropic laminate manufactured by the Quickstep process impacted at 30 J energy level

density difference, but resulted from intrinsic better mechanical properties.

Conclusions

2/2 twill weave MTM56/CF0300 composite was manufactured by conventional autoclave process and a novel process—the Quickstep process. The quasi-isotropic laminates $[45/0/–45/90]_{2S}$ were impacted at low energy levels 5, 11, 17, 24 and 30 J. Dye penetrant X-ray images showed less damage for laminates cured by Quickstep process than that cured by autoclave process. Matrix cracking, delamination, fibre breakage and fibre buckling failure modes were all observed from optical microscopy. Composite laminates cured by the autoclave showed extensive matrix fracture in the center of the lowest ply indicating the brittle property of the matrix material. The micro–debond test results showed better fibre matrix adhesion of the MTM56/CF0300 material cured by the Quickstep process.

The effect of the different thickness and density of laminates fabricated by two processes on the impact response was analyzed by using FEA. The simulation results showed that the higher thickness and lower density caused by processing induces higher stress on the center of the laminates which had a negative effect on the impact endurance. Furthermore, the better performance under impact loading for the Quickstep laminates was not caused by specimen geometry difference, but due to better mechanical properties.

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