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ASSESSMENT OF THE IMPACT PERFORMANCE OF REPAIRED THERMOPLASTIC LAMINATES

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Abstract

Thermoplastic composites with 45% by volume of fibres were prepared by using poly(lactic acid) as matrix and basalt woven fabrics as reinforcement. The effect on the laminate performance of a thermal repairing process after non perforating single or consecutive impact events was investigated. The first impact of a series was characterized by a lower value of the peak force, while the following impacts showed a higher peak and a steeper rise of the force, with a substantial superposition of all consecutive impact responses. The laminates showed some energy dissipation after the first impact at all energy levels, while successive impacts didn't show energy dissipation until 8 J.

The damaged laminates were then repaired at 100 °C and 175°C. Scanning laser Doppler vibrometry (SLDV) and microtomography (microCT) were used to assess the laminate damage. Both SLDV and microCT analyses confirmed that matrix continuity and woven fabric planarity were restored at the higher temperature. A second impact testing campaign on the same points demonstrated the complete recovery of the impact resistance after the thermal repairment at 175 °C.

1. Introduction

The composites market is dominated by thermosets composites, due to their high structural properties, but thermoplastic composites are characterized by better performances in damage tolerance and impact resistance, as well as higher productivity [1]. The high sensitivity of composites to hidden defects or damages can give rise to increasing damage during service life [2] and require continuous structural controls and rapid intervention in presence of damages. Cyclic loads or repeated impacts even of low entity, such as during service life or maintenance, can contribute to the onset and propagation of critical damages. The lower sensitivity to impact loads and the higher difficulty for crack growth, which can lead to unexpected laminate failure, is one of the main reasons for the ever growing interest in thermoplastic composites. Other advantages are the recyclability, high specific strength and stiffness, corrosion resistance, enhanced impact toughness, cost effectiveness and flexibility of design [3]. Conventional repairing approaches for damaged laminates make use of bolts, patches, gouges, or on gluing and stitching parts [4]-[10]. These methods can be expensive, and typically are excluded in case of small or barely visible damages, except that in high demanding applications. Thermoplastic composites allow to use conventional repairing methodologies but also exploit new repairing approaches thanks to the possibility to melt their matrix [11],[12].

Non-destructive evaluation (NDE) methods have an important role in post-manufacturing inspection of structures, for identifying damages during service, maintenance, or after repair. Optical inspection is the most simple, albeit very effective, technique [13],[14] but the most diffuse NDE techniques are based on ultrasounds [15]. Among them, scanning laser Doppler vibrometer (SLDV) can detect matrix damages through the excitation of the laminate by means of a surface bonded piezoelectric transducer and measures superficial strain by using a laser beam [14]. SLDV can precisely identify superficial discontinuities, and, with lower precision, estimate the damage extension through the laminate thickness. A very precise detection of through-thickness damages can be achieved by means of X-ray micro-computed tomography (mCT) [16]. In fibre reinforced composites micro-CT is particularly effective in detecting the internal spatial arrangement of fibres, as well as possible damages like delaminations and microcracking [17],[18].

In this paper a thermal treatment is used to recover not-perforating impact damages in the laminate. A reinforced composite based on poly(lactic acid) and basalt fibres woven fabrics was impacted at low energy and multiple times at the same impact point. A compression moulding process was used to repair the thermoplastic composite, and the effect of heating temperature was investigated by means of optical inspection, scanning laser Doppler vibrometry, and micro-computed tomography.

2. Experimental

2.1. Materials

Poly lactic acid - PLA (Luminy L175 from TotalCorbion NV, The Netherlands) was used as matrix. It has a glass transition temperature of 60°C and peak melting temperature of 175°C. The tensile modulus is 3.5 GPa and the tensile strength 50 MPa, as reported in the datasheet [19]. Basalt fibres (type BAS 220.1270.P) were supplied by Basaltex-Flocart NV (Belgium) in the form of a plain weave fabric with surface weight of 220 g/m², yarn count of 7.2 ends/cm (warp and weft) [20]. Basalt fibres density was 2.67 g/cm³, according to the ASTM D792 procedure.

2.2. Composite preparation and repairing

Composite plates were prepared by using the film stacking process. Layers of reinforcing fabric and PLA, 120 mm x 170 mm in size, were alternatively stacked and then pressed by using an hydraulic hot plate press. Laminates consisting of 10 balanced fabric layers 0°/90°, symmetrically arranged with respect to the middle plane of the laminate ([0/90]5_s configuration), were obtained with a thickness of 1.80 mm and fibre content target of 45% by volume. Compression at 180 °C at 0 MPa for two minutes and 0.5 MPa for five minutes was applied on the stacking sequence to impregnate the fibres. Composite repairing was performed by hot compacting damaged laminates at 100 °C or 175 °C for 5 minutes at near-zero pressure.

2.3. Laminate characterizations

Flexural properties were determined by using a three point bending configuration set according to ASTM D 790. A universal testing machine (mod. 4304 from SANS Shenzhen - China, now MTS Inc., USA) equipped with a 5 kN load cell was used. Out-of-plane impact tests were performed by using an instrumented drop-weight impact testing machine (model Fractovis Plus from CEAST – Italy) equipped with a hemispherical tip (diameter 12.7 mm). All tests were performed putting the specimen on a stainless steel annular ring (internal diameter 40 mm, outer diameter 60 mm). The impactor mass was 1.93 kg, and the impact energy, ranging between 1 and 8 J, was set by changing the impact height. Series of 4 consecutive impacts were also applied to investigate the sensitivity to multiple impacts of the composite. Three samples for each impact condition were tested.

2.4. Damage detection

Optical analysis in reflection mode was carried out by using a microscope (model Z16 APO, Leica Microsystems GmbH, Germany) to investigate the superficial damages induced on the composite. The scanning laser Doppler vibrometry (SLDV) acquisition was made with a single head of the PSV-400-3D vibromter from Polytec (Waldbronn, Germany), measuring the vibration velocity of the sample on

the non-impacted surface at grid points spaced about 2.2 mm. The samples were excited with a surface bonded piezoelectric transducers of 10-mm diameter and 0.5-mm thickness (CeramTec, Germany) that was placed on the impacted face at the middle of one of the short edges. The excitation signal (5-cycle long tone burst with 100 kHz central frequency) for the transducer was generated using an arbitrary waveform generator TGA1241 from TTI (Cambridgeshire, England) then amplified using the EPA-104 Piezo Linear Amplifier from Piezo Systems, Inc (Woburn, MA, USA). The sensed wave signals were filtered in the bandwidth 25-300 kHz by a bandpass filter and the signal root mean square (RMS) was calculated for each grid point [21].

Microtomographic image acquisition has been performed using an UltraTom CT scanner manufactured by RX Solutions (France), equipped with a Hamamatsu micro focus sealed X-ray tube operating at 70kV and 428 μ A. A 16 μ m spatial resolution was used for the acquisitions. The X-ray shadow projections are digitized with 65536 brightness gradations (16 bits) and recorded in TIFF image format. The image acquisition time was about 2h per specimen. For 3D reconstruction, X-ray images were acquired from 1440 rotation views over 360° of rotation (0.25° rotation step).

3. Results and discussion

The average fibre volume content of laminates was 45.8%. All laminates were free of voids. The absence of voids was qualitatively confirmed through optical microscopy and microCT reconstructed volumes. The prepared laminates exhibited a flexural modulus of 18.6 GPa, flexural stress of 213.3 MPa, and strain at break of 1.34 %. The low strain at break could be related to the possible low interface strength between PLA and basalt fibres, whose sizing treatment was not specifically developed for the used matrix.

Preliminary impact tests on laminates showed a perforation threshold higher than 8 J, hence that was set as limit for testing. Figure 1A shows the impact points at different impact energies. It is evident the increase in size of the damaged area. The force peak during impacts increased with the impact energy as well (Figure 1B). The widening of damaged area can also be associated with the increased energy dissipation during the impact, as evident from the residual value of the energy-displacement curves, which represent the un-recovered energy (Figure 1C).

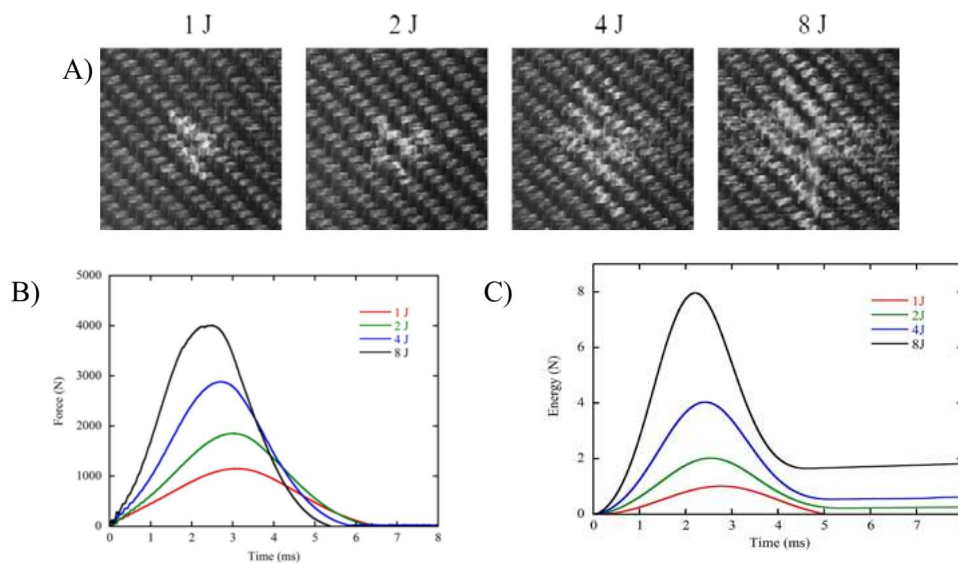


Figure 1. A) Appearance of the impact point at different impact energies; B) Force- and C) Energy-versus time curves as function of the impact energy.

The plots of consecutive impacts show a peculiar behaviour, because the force peak during the first impact is lower than that detected during the subsequent ones (Figure 2A, impacts at 4 J). Additionally, impacts following the first do not show residual dissipated energy up to 4 J (Figure 2B). This verifies at all impact energy values, and has been related to the fact that irreversible phenomena like matrix cracking and delaminations only occur after the first impact, while the subsequent ones do not induce further significant damages until 8 J is used.

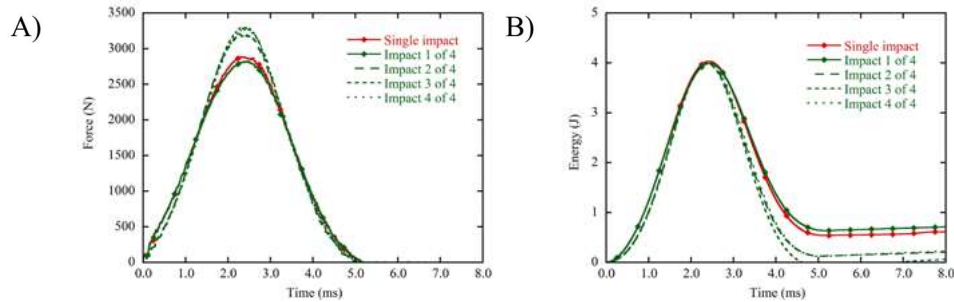


Figure 2. Energy versus time (A) and Force versus time (B) curves after 4 J impacts. Curves from first impacts have a diamond mark.

SLDV analysis evaluated the superficial damaged areas on the impacted surface after one (1x), two (2x) and four (4x) impacts at 4 J (Figure 3A). The damaged area (light grey and white pixels) increases with the impact energy and with the number of consecutive impacts. The optical analysis (Figure 4) shows that laminates processed below the melting temperature of PLA were only able to recover the laminate planarity, while superficial damages were still visible. On the contrary, laminates repaired at 175 °C were completely clean of superficial impact signs. This result is in agreement with the SLDV analysis, which shows residual damages in the laminate repaired at 100 °C (Figure 3B) and no damage pattern in the laminate repaired at 175 °C (Figure 3C). Finally, the microtomographic analysis confirmed the complete recovery of the woven fabrics planarity after both thermal treatments, and no sign of fibres deformation was evident (Figure 5). The combined use of SLDV and microCT results allow to say that thermal treatments were able to recover the reinforcement planarity, but only a temperature high enough to melt the matrix allowed to completely erase any sign of matrix and interface related damages.

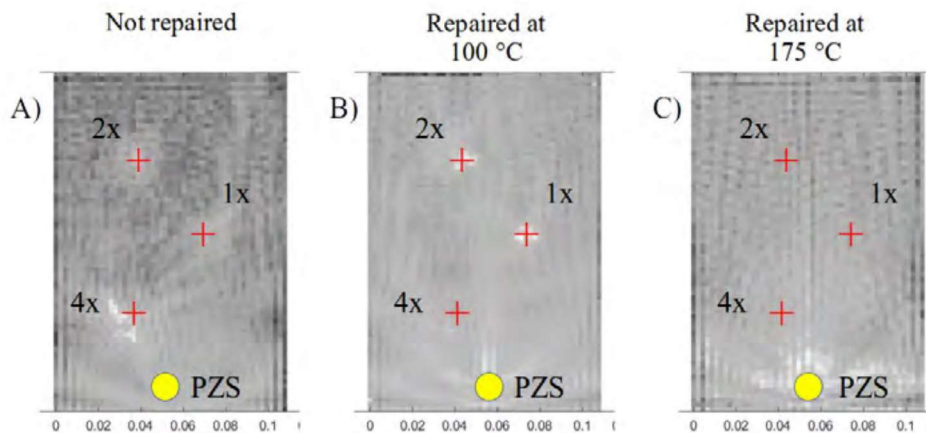


Figure 3. Scanning laser Doppler vibrometric analysis of laminates impacted at 4 J: A) Not repaired, B) repaired at 100 °C, C) repaired at 175 °C. The red cross is the impact point; 1x, 2x and 4x are the number of consecutive impacts. The yellow circle represents the position of the piezoelectric sensor (PZS).

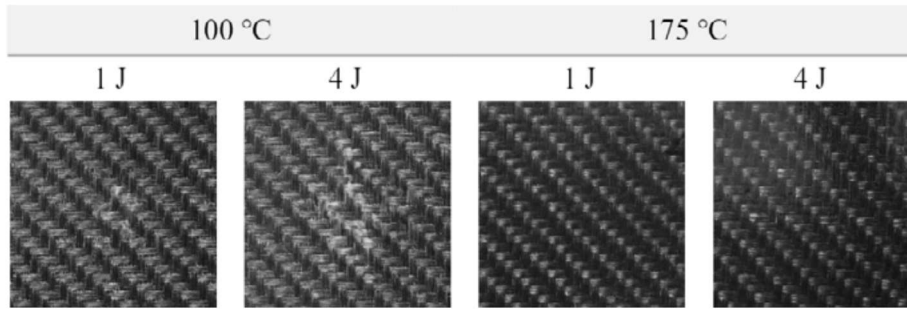


Figure 4. Impact points on front sides of repaired laminates. Square edge is 33 mm.

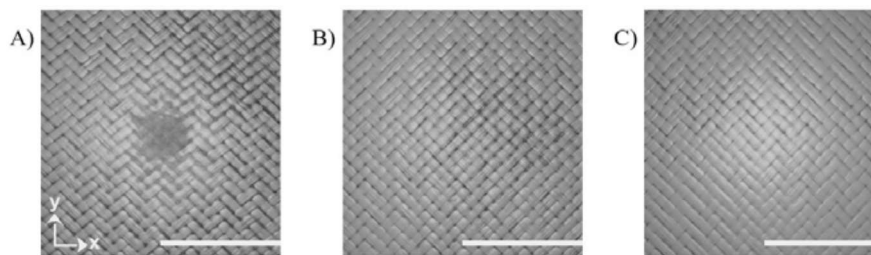


Figure 5. Top surface of microtomographic 3D reconstructions of laminates A) impacted four time at 4 J, b) repaired at 100 °C and c) repaired at 175 °C. White scale bar is 25 mm.

The second impact testing campaign on the same previously impacted points showed that the laminates repaired at 100 °C were still able to show a good performance but force peak values were significantly lower with respect to the first impacts series. On the contrary, the laminates repaired at the matrix melting temperature showed almost the same performances than before repairing, and this is remarkable when considering the fact that each repaired laminate received on each impact point twice the number of impacts with respect to the not repaired laminate.

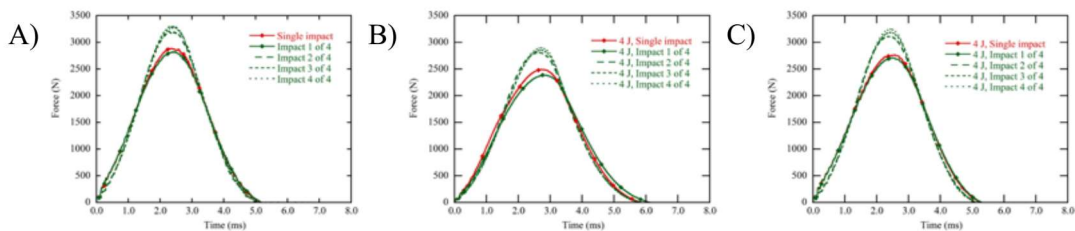


Figure 6. Force versus time curves of laminates impacted at 4 J before and after repairing: A) not repaired, B) repaired at 100 °C, C) repaired at 175 °C.

4. Conclusions

Composites based on PLA and basalt woven fabrics were impact tested at impact energies ranging between 1 and 8 J, and up to four consecutive impacts were delivered. Both front and back surfaces were damaged, and the damaged area increased with the impact energy. The first of each impact series was characterized by a lower peak force and a significant amount of unrecovered energy in proportion to the impact energy. Successive impacts showed a higher peak force and an almost negligible unrecovered energy until impact energy was equal to 8 J.

The laminates were repaired at 100 °C and 175 °C. Microtomographic analysis showed planar woven fabrics at both temperatures. On the contrary, the scanning laser Doppler vibrometry showed that only the higher temperature allowed to erase any visible and instrumental sign of damage. Both techniques combined allowed to assess that a high molecular mobility is needed to successfully restore both matrix continuity and woven fabric planarity.

The effectiveness of the repairing process was finally assessed by a second testing campaign on repaired laminates, and was performed on the previously impacted points. The impact behaviour of laminates repaired at 175 °C was almost superimposed to that of pristine laminates, confirming a complete recovery of the mechanical performance under impact.

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