EFFECT OF TEMPERATURE AND MWCNTs ON LOW VELOCITY IMPACT RESPONSE OF CFRP LAMINATES

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Abstract

This experimental work addresses the effect of temperature and MWCNTs on the response of carbon fibre reinforced epoxy matrix (CFRP) laminates under low impact velocity. The test temperature ranged from +80 °C down to -40 °C while two sample configurations were examined, namely cross-ply and quasi-isotropic. Results showed the influence of temperature and of stacking sequence on the impact response of CFRP. The presence of carbon nanotubes, despite a larger delaminated area, provided the quasi-isotropic structure with an increased damage tolerance, ascribed to the enhancement of mode II interlaminar fracture toughness.

1. Introduction

Carbon fibre reinforced polymer (CFRP) composites are attractive in many structural applications like aerospace, automotive, marine etc. due to the high specific tensile strength and modulus, high dimensional stability and fatigue strength. However, the poor impact resistance is one of the major concerns of CFRP composite structures, which is due to their poor z-direction mechanical properties ascribed to the unreinforced neat polymer region at ply interfaces. It is not surprising that a number of researches have already been completed to improve the impact resistance and damage tolerance of fibre-reinforced composites using different approaches including 3D weaving, stitching and Z-pinning [1, 2]. These solutions are often associated with unavoidable and significant decrease of in-plane mechanical properties due to damage, fibre volume loss and stress concentrations due to micron-diameters pin insertion.

Recently researchers have focused their attention on nanofillers (such as carbon nanofibres, nanoclays and carbon nanotubes (CNTs)) in order to enhance the inter-laminar properties and, as a consequence, the impact resistance of composite. During a low velocity impact on a composite laminate, four major failure modes can sequentially occur: matrix mode, in which cracking occurs at various angles to the fibres due to tension; compression or shear, where delamination mode produced by interlaminar stresses takes place only after the generation of a matrix crack; fibre failure in tension and in compression (fibre buckling) and penetration, once the impactor completely punctures the structure. The first two modes result from a combined in plane mixed mode interlaminar fracture, therefore the composite material impact resistance may be improved by enhancing the fracture energy or delamination resistance under the two in-plane modes of fracture. In a non-penetrating impact event the predominant mode is the mode II shear failure, while the mode I tensile component of the delamination driving force is usually lower compared to mode II shear component [3]. Previous research efforts have indicated that there is a good possibility for the improvement of interlaminar and intralaminar strength of CFRPs via the incorporation of CNTs into the polymer matrix [4-6]. It is therefore believed that the positive effects of nanofillers on mode II fracture properties of composites can be directly transferred to their impact properties. In literature there are several works addressing this issue, even if often conflicting results can be found. Hosur et al. [7] examined the impact response of plain weave carbon/epoxy composite laminates doped with organically modified montmorillonite nanoclay. They reported no change in the impact response up to a 3 wt% of nanoclays, even though the presence of nanoclays reduced the damage size. Iqbal et al. [8] tested $[0/90]_{3S}$ CFRP with nanoclay and found that incorporation of nanoclay up to 3 wt% in the matrix lowered the impact damage size compared with neat epoxy laminates and both the damage resistance and damage tolerance of the laminates were enhanced. However, nanoclay showed only a marginal effect on the impact response. Soliman et al. [9] reported significant improvements in terms of impact response and damage size in woven carbon fibre composites doped with functionalized MWCNTs. In Kostopoulos et al. [10] the epoxy matrix of a carbon fibre composite with quasi-isotropic $[0, +45, 90, -45]_{2s}$ stacking sequence was reinforced with 0.5 wt% of MWCNTs. The authors concluded that delaminated area decreased for the doped samples but results showed a large standard deviation. In addition, the specific delamination energy (SDE) was superior only at higher impact energy levels for the modified samples, suggesting that the CNTs perform better at higher strain rates. Siegfried et al. [11] investigated the effect of carbon nanotubes on the impact and after impact performance of woven (twill 2/2) carbon fibre/epoxy composites. Nanotubes were found to improve the mode II interlaminar fracture toughness and (with it) damage tolerance of composites, but they also made composites more susceptible to the onset of matrix cracks leading to a larger delamination area after impact. A feature common to all these studies is the important role played by the degree of dispersion of the nanofillers in the matrix. The effect of temperature on nano-modified laminates, another important variable in determing the impact response of such composite structures, has been scarcely investigated in literature.

In this framework, the aim of this experimental work is to show the effect of MWCNTs on the impact properties of carbon fibre/epoxy composite laminates using a nano-modified prepreg compatible with the industrially accepted autoclave forming process as a function of stacking sequence and impact temperature.

2. Materials and methods

2.1. Materials and production of composite plates

Carbon fibre reinforced laminates are based on Arovex® 250 Prepreg, which is a curing carbon nanotube strengthened epoxy prepreg. In particular, Arovex 250 resin contains an optimum level of carbon nanotubes for additional toughness and enhanced mechanical properties. The carbon nanotubes use molecular dispersion technology to ensure an even distribution throughout the resin. Control samples were also fabricated by autoclave forming without carbon nanotubes. Two different stacking sequences with 16 plies, cross-ply (CP, $[0/90]_{4s}$) and quasi-isotropic (QI, $[0/\pm45/90]_{2s}$), have been investigated, with a final target thickness of 2.00 ± 0.05 mm.

2.2 Impact testing

Impact tests were performed using an Instron instrumented drop tower (CEAST 9350 model) equipped with an hemispherical steel impactor having a diameter of 12.7 mm. A circular sample holder with an inner diameter of 40 mm was used to support the specimen, in combination with a clamping plate – pneumatically activated – having the same inner diameter. This configuration is in agreement with the requirements of the ASTM D5628 standard, geometry FE. A set of specimens have been initially tested at room temperature with three impact energies (2.5, 5.0 and 7.5 J) by keeping constant the total mass (3 kg) while changing the drop height.

Then, in order to assess the effect of temperature on the impact resistance and related damage modes, additional low velocity impact tests were performed at -40 °C and +80 °C. In this case, each specimen was conditioned inside a thermostatic chamber embedded in the drop tower system for 1 hour at the test temperature prior to impact. The impact conditions used for room-temperature testing have been maintained unchanged for non-ambient testing too.

2.3 Non-destructive evaluation of impact damage and flexural strength

The impacted plates were inspected by a non-contact profilometer (Taylor-Hobson Talyscan 150) in order to measure the dent depth of each coupon and determine the barely visible impact damage (BVID) threshold. Ultrasonic inspection (C-scan) was conducted after low velocity impacts to measure the delaminated area. Ultrasonic testing (OmniScan MX) is performed with a phased array probe 3.5 MHz, 64 elements, pitch 1 mm, active aperture 64 mm, elevation 7 mm, water immersion with 25 mm water wedge. The damaged area (mm^2) for each is considered through-the-thickness as the sum of the damaged areas in each layer.

As far as concerning flexural strenght evaluation, four-point bending tests were performed in accordance with ASTM D 6272 on a machine equipped with a 10 kN load cell (Zwick/Roell Z010). Specimens have been tested in bending configuration either after their production (non impacted samples) or after the low-velocity impact tests to measure their residual flexural properties.

3. Results and discussion

The impact and post-impact performance of the neat and modified (with the addition of CNTs) composite laminates were evaluated using several parameters that are commonly used in literature. These parameters include the peak force and the absorbed energy from the impact tests, the delaminated area (as measured by C-scan), together with the flexural strength and modulus after impact.

Fig. 1 shows the typical force and energy histories for the different stacking sequences for impacts performed at room temperature. The global behaviour of the neat and modified CFRP laminates did not show any significant difference.

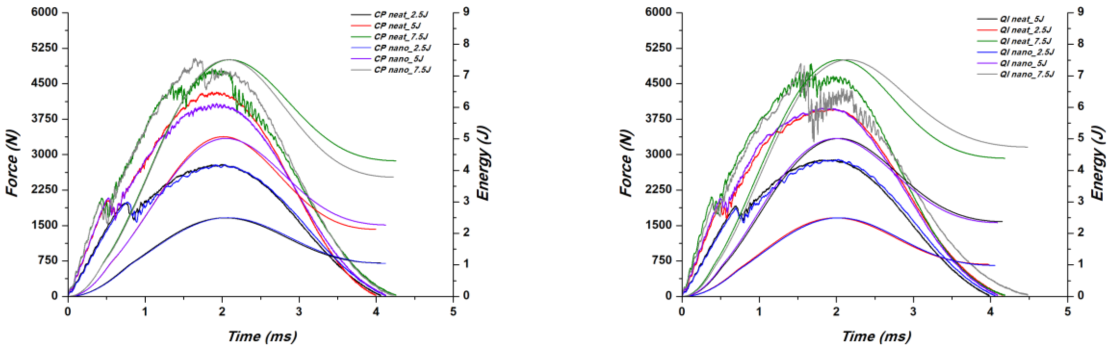


Figure 1. Force and energy responses at different impact energies at room temperature for neat and nano-modified laminates with QI and CP stacking sequences.

Both stacking sequences exhibited a similar impact response, with significant damage induced only by a 7.5 J-impact. Inspection of the damaged area on the surface by naked eye indicated that the samples of all configurations, irrespective of the presence of CNTs, were all damaged in a similar way. On the impacted surface, transverse matrix cracks were found in CP samples around the dent for impacts at energies from 5.0 J on, whilst in QI samples only a dent with no cracks was noted. This dent depth was found to be higher for neat specimens compared to doped ones, especially at the highest energy applied. Nano doped CP samples did not reached the BVID threshold for an impact energy of 7.5 J, while neat CP and QI samples (nano or neat) at 7.5 J exhibited a dent depth higher than 0.3 mm, which is generally accepted as the threshold of detectability, being BVID subjective by nature. From the analysis of the impacted specimens rear side, we concluded that fibre breakage (much more severe in QI samples) was visible in all laminates. Differences in absorbed energy values among the different materials appeared to be limited and no major trend can be highlighted. Contact duration was consistently found higher for doped laminates, with the highest values showed by QI laminates. This could be a consequence of the larger delaminated areas and the associated loss of the composite bending stiffness. This trend was confirmed by C-scan results too. Fig. 2 summarizes the projected delaminated areas as a function of impact energy.

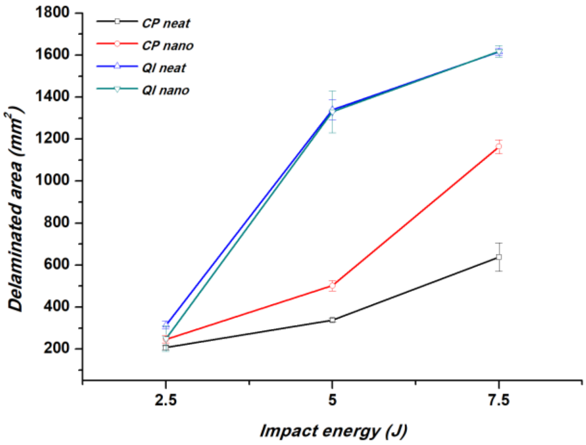


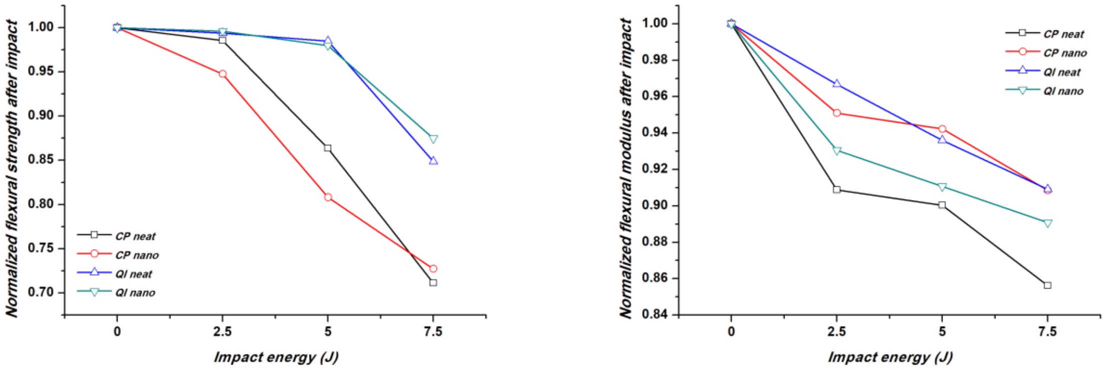
Figure 2. Delaminated area as a function of impact energy and laminate configuration

QI laminates exhibited a larger internal damage compared to CP laminates but the presence of CNTs did not offered any significant reduction in damage extension. On the contrary, for CP laminates the delaminated area substantially increased when CNTs were added. The energy required for delamination initiation is usually shared in two components, one of which pertains to the flexural deformation of the specimen, and the other to the local deformation at the contact point, being the latter more and more important with increasing thickness. For thin laminates, like the ones investigated in the present study, the damages are likely to be driven by the high flexural stresses. The increased flexibility of the structure triggers new intra-ply damage in the form of matrix cracks wich increases the interlaminar shears, thus promoting new discrete damage between adjacent plies. It is supposed that CNTs are not so effective when the matrix is loaded in compression and shear, which are common loading patterns during an impact event [11].

As shown in Fig. 2, the delaminated area for all CNT modified laminates was larger compared to the reference composite and, as a consequence, this would lead to a lower flexural strength after impact. This is confirmed for CP laminates but it is worth mentioning that the residual strength of QI doped laminates was higher, as can be cleary seen in Fig. 3.

The fact that nano modified QI laminates have an higher residual strength despite larger delaminations indicate that they have higher damage tolerance than the other tested laminates, even higher than the reference composites. CNTs can enhance the properties of composites due to toughening mechanisms such as crack bridging and CNT pull-out, mainly confined in the resin rich areas.

Stacking sequence played an important role in the behaviour of CFRP composites under impact loading at different thermal conditions. In particular, temperature affected both the peak force and the absorbed energy. In nano modified QI samples the effect on peak force was rather limited while it became more significant in neat QI laminates, where at -40 °C and for a 7.5 J-impact the peak force significantly decreased compared to the room temperature impacts (Fig. 4).



(a) (b)

Figure 3. (a) Residual normalized flexural strength and (b) stiffness as a function of impact energy

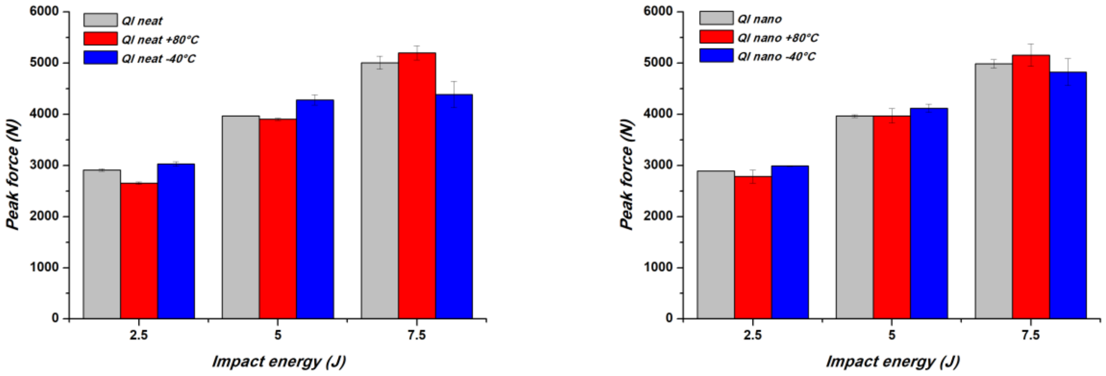


Figure 4. Peak force as a function of impact energy for QI neat and QI nano laminates

CP samples exhibited an even higher dependence on temperature in terms of a decrease in peak force both at +80 and -40 °C. As temperature increases, the absorbed energy did as well, as confirmed by the increased value of the damage degree, defined as the ratio of the absorbed energy to the impact energy. This is an expected result due to the epoxy being more ductile at higher temperatures. More ductility leads to increased plastic deformation; therefore at higher temperatures, there is less elastic strain energy that can be returned to the impactor, resulting in greater absorbed energy values. This trend is general, irrespective of the presence of CNTs, even though a slightly lower damage degree was recorded for doped laminates.

The absorbed energy was found to increase as temperature decreased, observation that applies to all laminates and impact energies but is especially true at the highest impact energy used. The influence of temperature on the absorbed energy by the laminate during impact may be due to the lower specific fracture energy of the material at low temperature. The embrittlement of the polymeric matrix along with the interlaminar thermal stresses generated in the laminate at low temperature (due to mismatch in thermal expansion coefficient and material stiffness in the direction of fibres and in the transverse direction) [12] can facilitate the nucleation and propagation of damage (mainly as matrix cracking) when subject to impulsive loading. In this regard, the presence of CNTs does not provide any significant enhancement.

4. Conclusions

Quasi-isotropic and cross-ply laminates using a commercial prepreg modified with MWCNTs were manufactured by vacuum bagging followed by consolidation in autoclave. Composites were subjected to low velocity impact tests at three different temperatures, namely room temperature, +80 and -40 °C, non-destructively examined and subsequently tested under four-point bending. Interestingly, at low velocity impact no significant difference was noted in the general impact response, and nano modified QI laminates exhibited an even higher delaminated area compared to the reference material. However, CNTs improved the properties of composites, depending on the particular stacking sequence, due to toughening mechanisms that can hinder delamination growth once nucleated, particularly in QI laminates. These mechanisms seem to be less effective at low temperatures, where interlaminar residual thermal stresses can accelerate matrix cracking during low velocity impact that triggers delaminations no more counteracted by the decreased mode II fracture toughness.

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