FATIGUE BEHAVIOUR OF CARBON FIBRE/EPOXY COMPOSITE MANUFACTURED BY VACUUM ASSISTED COMPRESSION RESIN TRANSFER MOULDING

L.Aretxabaleta*****, J. Aurrekoetxea, M. Iragi, G. Aretxaga, M.A. Sarrionandia
[1] Mechanical Engineering and Industrial Manufacturing Department, Mondragon Unibertsitatea, Mondragon, Spain
* Corresponding author(laretxabaleta@eps.mondragon.edu)

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Abstract

Carbon fibre reinforced epoxy composites were successfully manufactured by a new vacuum assisted compression resin transfer moulding process (VACRTM). The high fibre volume fraction and low void content are promising properties for structural applications. The fatigue life curves for the on-axis and bias directions were determined, and it was found that even at 45% of the material strength, fatigue life in both directions exceeds 5×106 cycles. Instrumented falling weight impact tests were also carried out. Damage initiation impact energy threshold was found to be 1.4 J and total penetration energy threshold was above 20 J. Repeated low energy instrumented falling weight impacts were also carried out, and it was found that around an impact energy of 8,5 J there was an important decrease of the number of impact that the samples can support befor breaking.

1. Introduction

Carbon fibre reinforced epoxy composites have gained substantial interest over the last years, mainly due to their high specific stiffness and strength, high impact energy absorption per unit of weight, noise suppression capabilities and excellent resistance to fatigue [1,2]. The high operational costs involved in combination with the intricacy of the manufacturing techniques currently employed have restricted wider industrial use of composites. For that reason, considerable effort has been made in the direction of finding and developing alternative cost-effective routes for manufacturing composite materials. Resin transfer moulding (RTM) of thermoset polymers is a well-established processing method for niche applications [3]. The RTM process provides various advantages in producing high-performance composites such as non-expensive process equipment, excellent control on mechanical properties, closed mould process, low filling pressures, possibility of incorporation of metal inserts and attachments, possibility of producing large and complex parts and low labour costs. However, there are still some difficulties in the manufacturing of parts having a high fibre content (typically greater than 40% for structural applications). Increasing the fibre content decreases the permeability of the preform, leading to long filling time, incomplete impregnation and high void content.

In order to overcome the earlier mentioned problems in RTM, several strategies have been presented to modify the conventional RTM process (increasing the injection pressure, decreasing the resin viscosity or multiple gate injection). Another effective improvement in RTM to reduce simultaneously the mould filling time and void content is to combine the compression into the resin transfer moulding. This process is called compression resin transfer moulding (CRTM) and can be a suitable technique to manufacture structural composites having most of advantages of RTM [4-9]. In CRTM, unlike in conventional RTM, the mould is only partially closed when resin injection begins. This increases the cross-sectional area available for the resin flow, and decreases flow resistance by providing high porosity in the reinforcement. In some cases, the mould is opened so that there is a small gap between the fibre surface and the mould wall which facilitates further the resin flow. Once the required amount of resin is injected into the gap and the gate

is closed, the mould platen moves down to close the mould and squeeze the resin into the preform, which also undergoes compaction to achieve the desired volume fraction. Therefore, instead of going through the entire fibre stacking in the planar directions as in RTM, the CRTM process wets the fibrous reinforcement by penetrating in the thickness direction. The recent research activities have been focused on the analysis of the filling stage of CRTM moulds [4-9], and for the mechanical behaviour limited research has been presented.
The aim of the present paper is to investigate the microstructure and performance of the carbon fibre reinforced composite manufactured by a new vacuum assisted CRTM process (VACRTM). The performance evaluation will involve quasi-static tensile, fatigue and impact tests. This will be accompanied with the investigation of the microstructure (fibre wet-out, void content) and failure mechanisms (interfacial bonding between the carbon fibre and matrix).

2. Experimental

2.1. Materials

The thermosetting system used in this study was an epoxy EPOLAM 5015 and EPOLAM 5014 hardener (supplied by Axson). The resin/hardener mix ratio was 100:34 parts by weight. In order to remove air bubbles created at the initial resin-hardener mixing stage, the mixture was left for 10–15 min under vacuum.
The reinforcement used was high strength carbon fibre fabric with plain weave architecture and has a surface weight of 193 g/m^2 (supplied by Axson, ref. 43192).

2.2. Composite processing

Various stages in VACRTM are so identical to conventional CRTM except the filling stage, since vacuum is applied to the partially open mould. The preform (fourteen layers) is placed in the mould (80 ºC). The mould is then partially closed, creating a gap of 2 mm between the mould plates and preform. The vacuum (650 mmHg) is generated into the mould from the two output gates (Fig. 1). Resin is injected from the central injection gate with a pressure of 20 bar. Once the required amount of resin is injected into the gap, the injection point and one of the output gates are closed, and the mould plates move down to close the mould to achieve the desired laminate thickness (2.5 mm). This compression stage is monitored by displacement. The compression stage is important for structural applications, because it significantly increases the fibre volume fraction and reduces the void content. Flat plates 350 x 250 x 2.5 mm³ of composite were successfully produced.

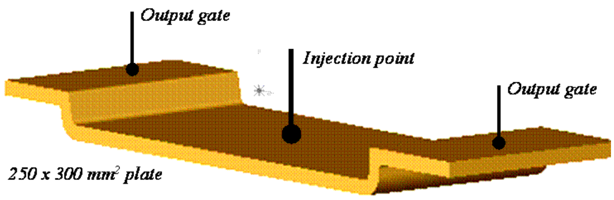

Figure 1. Schematic representation of the mould design.

2.3. Tensile-tensile fatigue tests

Tensile-tensile fatigue test were performed on a MTS 810 machine equipped with a 100 kN load cell. All fatigue tests were carried out at a constant load amplitude, using a sinusoidal waveform with a frequency f = 6 Hz, which minimise the generation of hysteretic heat in the specimen volume. All the tests were run at a stress ratio R ($\sigma_{min}/\sigma_{max}$) = +0.1 with different maximum stress ratios S_{max} (=σ_{max}/σ_c). The maximum and minimum applied stresses are σ_{max} and σ_{min} respectively, and σ_c is the damage initiation stress. Due to limitation in time, the numbers of fatigue cycles were limited to 5 million cycles.
The specimen geometry employed was that chosen for the quasi-static tensile tests.

2.4. Impact tests

Impact tests were performed in an instrumented falling weight impact test machine. A semi-spherical indenter of 20 mm diameter and 2.045 kg mass was used and force-time curves were recorded. Plates were tested at an impact height corresponding to a sub-critical behaviour (no damage), considered as the reference test. After that, the same samples were tested at different super-critical impact heights, and finally the reference sub-critical test was repeated on each of the samples. The loss of contact stiffness, measured as an increase of contact time, indicates the relative damage produced by the second super-critical test. The sub-critical test used as a reference was carried out at an impact height of 50 mm (1 J), and super critical tests corresponded to impact heights of 70 mm (1.4 J), 250 mm (5.01 J), 500 mm (10.03 J) and 1000 mm (20.06 J).

Fatigue instrumented falling weight impact tests (repeated low energy impacts above first damage threshold) were also performed to determine the reduction of mechanical properties of the material due to damage in terms of the number of impacts. These tests were carried out at impact heights of 175 mm (3.51 J), 300 mm (6.02 J), 400 mm (8.02 J), 410 mm (8.22 J), 425 mm (8.52 J), 450 mm (9.03 J) and 500 mm (10.03 J). Peak force and dissipated energy with respect to the number of impacts were registered, as well as the number of impacts needed to produce the total failure of the sample with respect to the impact energy.

3. Results and discussion

3.1. Tensile-tensile fatigue test

The fatigue behaviour of the on-axis direction is fibre dependent, so the fatigue curve is very flat. For S_{max}~0.85 the number of fatigue cycles to failure (N_f) is approximately 16500 cycles, whereas for S_{max}~0.78 N_f is higher than 5 million cycles.

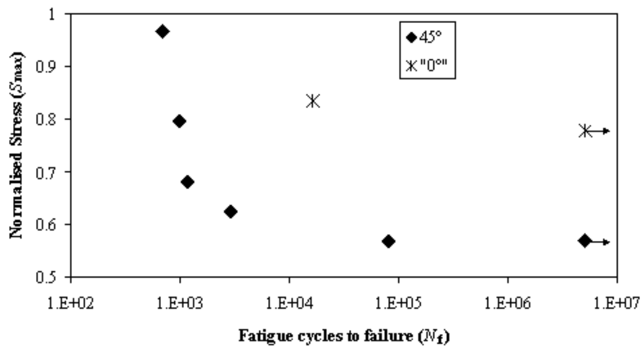

Figure 2. Tensile-tensile fatigue curve for 45º specimens.

Fig. 2 shows *S-N* curve of the bias direction specimens. Based on fatigue life, the fatigue properties are much lower than in the on-axis direction. The stress level corresponding to the damage initiation point in bias direction is very close to the maximum stress level. Consequently, it is not surprising that the fatigue life of the samples at S_{max}~0.9 is very small (<1000 cycles). For S_{max}~0.57 stress level fatigue life exceeds 5×10^6 cycles.

3.2. Falling weight impact tests

In Fig. 3 *F-t* curves at different impact heights are shown. These curves correspond to sub critical tests carried out at an impact height of 50 mm (indicated as “Ref” in the graph), but on previously tested samples in super critical conditions. The impact heights at which the previous super critical tests have been performed are indicated in the graph. It is shown that for an impact height of 70 mm the peak force decreases and contact time increases slightly, which indicates the presence of a small damage area in the material. For higher impact heights of 250, 500 and 1000 mm the damage area increases drastically which is represented as a loss of the stiffness (a decrease of the peak force and an increase of the contact time) in the material. It can be seen that the stiffness loss is not proportional to the impact height, being higher in the range of impact height from 70 to 500 mm than from 500 to 1000mm.

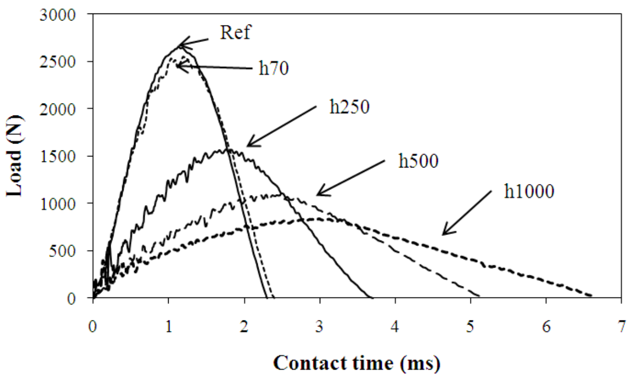

Figure 3. *F-t* curves of sub critical falling weight impact heights below 70 mm (Ref) and impact heights of 70, 250, 500 and 1000 mm.

In Fig. 4 the ratio of the contact time of the sub critical tests performed on previously super critically tested samples is shown, with respect to the super critical impact energy. It can be seen that for small super critical impact energies (< 5 J) the reduction of the contact time with respect to the reference contact time is not very significant. Between 5 and 10 J the contact time loss with respect the reference sub critical test is about a 60 %, so the maximum damage increase happens in this energy range. Above a super critical impact energy of 10 J again the loss of contact time is less significant.

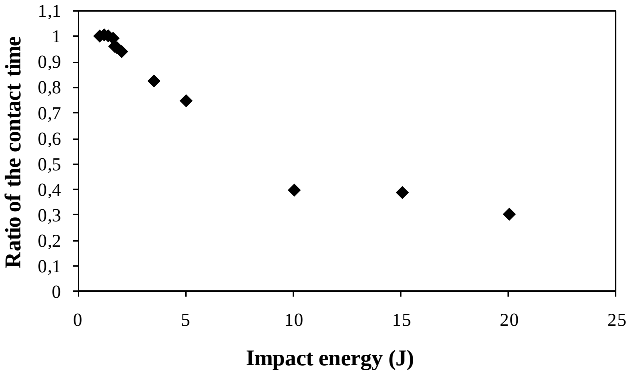

Figure 4. Ratio of contact time of sub critically tested samples with respect to the impact energy of previously performed super critical tests.

Repeated instrumented falling weight impacts have also been carried out at low energies. It is expected that the material will lose most of its capability of supporting fatigue impact conditions in the range of impact energies between 5 and 10 J.

In Fig. 5 the number of impacts needed to produce the total failure of the sample are presented with respect to the initial impact energy. It can be seen that below an impact energy of 8.02 J the samples do not break until the maximum number of repeated impacts. This value for unbroken samples varies; the highest energy level without rupture (8.02 J) has been tested 125 times, while for lower impact energies only 50 tests have been carried out, since it is assumed that they will support more than 125 impacts without rupture. For the next higher impact energy of 8.02 J, the number of impacts for rupture has been 66, while for an impact energy of 8.52 J, 13 impacts have been enough to produce sample rupture. These results agree the ones shown in Fig. 4 which indicate that the impact energy range where most of the damage is induced in the material is between 5 and 10 J.

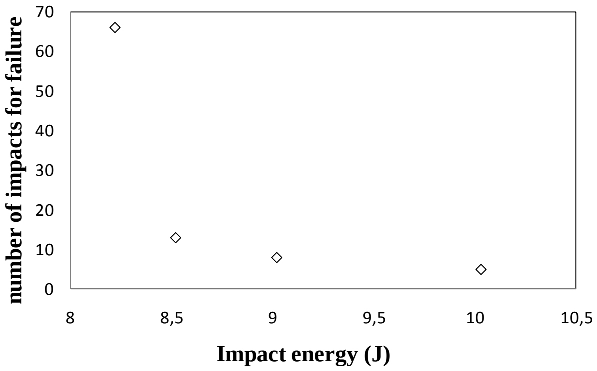

Figure 5. Number of repeated impacts for sample rupture with respect to the initial impact energy.

In Fig. 6 the evolution of peak force is shown with respect to the number of impacts for different impact energies. For all the impact energies peak forces for the first test repetitions are similar, and these values decrease drastically in the first 20 repetitions. After that, peak force stabilizes showing the tendency to a higher peak force for higher impact energies.

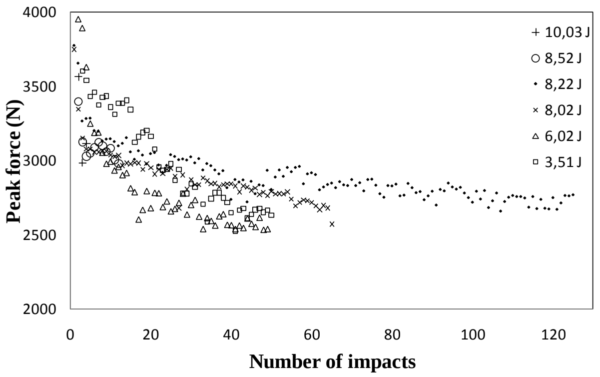

Figure 6. Evolution of the peak force with respect to the number of impacts for different impact energies.

In Fig. 7, dissipated energy is shown with respect to the number of impact repetitions, for the different impact energies. It can be seen that for low impact energies the energy dissipation is small, and as impact energy increases, so does the dissipated energy. This tendency is coherent with the fact that composite materials dissipate impact energy through damage mechanisms, and the damage induced in the material in impact tests is directly related to impact energy, as previously has been shown.

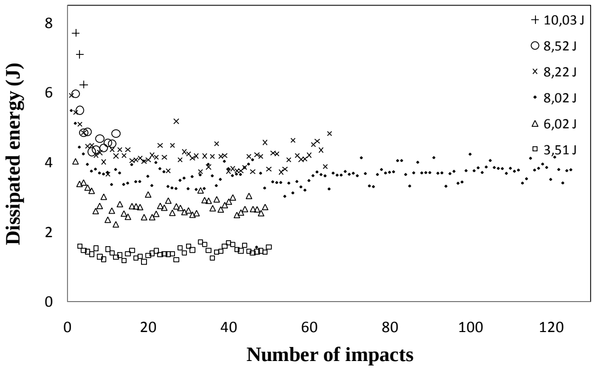

Figure 7. Evolution of the dissipated energy of each repeated test with respect to the number of impacts for different impact energies.

4. Conclusions

Carbon fibre reinforced epoxy composites were successfully manufactured by a new vacuum assisted compression resin transfer moulding process (VACRTM). The high fibre volume fraction (58.1%) and low void content (0.11%) are promising properties for structural applications. The measured stiffness is very similar to the theoretical values for the fibre content of the composites. The on-axis strength is 656 MPa, whereas at bias direction is much lower (183 MPa). The damage initiation stresses for on-axis and bias direction are 360 MPa and 176 MPa, respectively. The fatigue life curves for the on-axis and bias directions were determined, and it was found that even at 45% of the material strength, the fatigue life in both directions exceeds 5×10^6 cycles. Impact characterisation has shown that the damage initiation impact energy threshold for first damage is 1.4 J and the penetration energy threshold is above 20 J. Impact induced damage has been characterized through the loss of stiffness of the tested samples, identifying an impact energy range between 5 and 10 J where this value is a 60 % of the non damaged one. This in accordance with the fact that around impact energy of 8.51 J, the number of impacts needed to break the sample decreases drastically. Finally, at higher impact energies the dissipated energy in repeated impacts is higher, which is directly related to the amount of damaged material quantity.

Acknowledgments
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