Experimental Investigation into Quasi-Static Crushing of CFRP Composite Cylindrical Tubes after Thermal Aging

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Abstract - For the effective design of polymeric composites, designers need not only to make sure that they meet specific mechanical property criteria but also to consider the impact of environmental factors, which limit the development of safe and economical designs. As one of the expected environmental factors during the composite service life, thermal aging is addressed in the current paper for composite tubes subjected to crushing loading. In the present experimental study, tubes of carbon/epoxy composites were subjected to thermal aging at 90ºC, 120 ºC, 150 ºC, and 180 ºC before being subjected to quasi-static crushing. Besides, non-aged specimens were tested for comparison. The results showed that thermal aging has no effects on the load-displacement profile and crushing mode. On the other hand, the crashworthiness, assessed by the peak load, the energy absorbed and the specific energy absorbed, decreased by increasing the aging temperature to 120 ºC, due to thermal fatigue of the matrix and the fiber/matrix interface. At 150 ºC (the closest value to the T_g), the crashworthiness improved as a result of the post-curing process. After that temperature, the crashworthiness parameters reduced as a result of chain rupture and matrix oxidation. Based on these results, the designer needs to consider 10-15% margins in the energy absorption of carbon fiber-reinforced plastic (CFRP) composites to compensate for the thermal aging effect.

Keywords: Thermal Aging; CFRP composites; Crushing; Energy Absorption

1. Introduction

Nowadays, Fiber Reinforced Polymers (FRPs) are used to produce parts of aircraft, marine, and automotive structures to reduce overall weight, with adequate strength and stiffness, and reduce CO2 emission as well as improving the fuel efficiency [1]. Energy absorbers are used in automotive mainly to absorb the collision energy in a controlled manner in accidents before transferring it to the passenger compartment, which increases passenger safety. Traditionally, metallic structures have been extensively considered as energy absorbers because of their significant plastic deformation characteristics and capabilities in processing. Nowadays, composites are being used widely in these structures due to its ability to consume the impact energy in different damage mechanisms [2].

Several factors affect the crushing response of FRP composite tubes. These factors include the fiber orientation, the tube geometry, the fiber and matrix material, the crushing speed, the triggering mechanism, the filler, and the impactors' geometry [3]. When exposed to environmental effects, various physical, and chemical reactions may occur in FRP composites, causing degradation of their mechanical, physical and chemical properties [4]. The viscoelasticity of the matrix material substantially influences the temperature dependence of polymeric composites. When the ambient temperature is near/above the glass transition temperature T_g, the resin matrix softens, transitioning from a glass-like material into a rubber-like material [5]. In this case, the resin matrix cannot provide sufficient stress transfer between the fibers and the matrix, resulting in reduced matrix stiffness and a degraded fiber-matrix interface [6]. In the literature, several authors studied the effect of thermal aging on tensile [6], compression [7], bending [8], and impact [9] properties of FRP composites. To the authors best of knowledge, data available on the crushing after thermal aging of FRP composites is very limited [10]. The aim is to study the effect of thermal aging on the crushing characteristics (both crushing and post-crushing stages) of the CFRP composite tube by the quasi-static axial compression test.

2. Material and Test Specimen

Roll wrapped unidirectional tubes, manufactured by DragonPlate™, are used in the current analysis. This high strength to weight carbon fiber tubing is fabricated from unidirectional carbon fiber. The layers are oriented to provide high bending stiffness and axial strength and high hoop strength (resistance to crushing from a side load). The composite tube is made of carbon fiber of 2.3 x 105 MPa elastic modulus and 4800 MPa ultimate strength with a matrix glass transition temperature of T_g = 160 ºC. The tubes were delivered as one beam of 1200 mm length, 25.4 mm inner diameter, and 1.143 mm wall thickness. Each tube was sliced into the desired specimens' height of 60 mm using a computer-controlled abrasive cutting machine.

Parts of the tubes were cut and used to estimate the fiber volume fraction. The cut samples were measured (mass and volume) and subjected to ignition, as per the ASTM D3171. After ignition, the fibers remained in the container, where its mass was used to estimate the fiber volume fraction. Five samples were measured using the current methodology, and the result was that the fiber volume fraction v_f = 54.1% with a standard deviation of 2.6%.

3. Thermal Aging

The effect of temperature aging on the crushing behavior of composite tubes was studied using an insulated temperature-controlled air oven (JS0F-150) to provide high-temperature environments. Specimens were subjected to a constant temperature for six hours, the constant aging time used for the current study. The aging temperature values were 23 ºC (RT), 90 ºC, 120 ºC, 150 ºC, and 180 ºC. It is well-established that the aging temperature effect is highly dependent on the value of the T_g [11]. Consequently, the values of the temperatures were selected to have most of the readings before the T_g and one reading after the Tg. During its working conditions, composites are usually subjected to temperatures that are mostly below the T_g. However, in some cases, during its service time, composites can be subjected to temperatures higher than its glass-transition temperature [12]. The mass values of the specimens were measured before and after the thermal exposure, and the values are recorded in Table 1. The values listed in Table 1 are the average per three samples tested at each temperature. The differences in the mass with the different temperature shows an insignificant effect, which can be justified with the short aging time, compared to the data available in the literature [13].

Table 1: Average mass of the CFRP composite tubes before and after the thermal aging.

Temperature (ºC)	Mass before (g)	Mass after (g)	Difference in mass	
			Percentage	Standard deviation
90	8.77	8.73	0.4	0.08
120	9.03	8.99	0.37	0.05
150	8.14	8.11	0.37	0.01
180	8.08	8.05	0.37	0.12

4. Quasi-Static Crushing Tests

Quasi-static crushing tests were performed to assess the crushing capabilities of the composite tubes after thermal aging. The tests were conducted using an Instron 8500 digital testing machine with a full-scale load range of 250 kN. Two steel platens were set parallel to each other before starting the test, and the behavior of each specimen under compression was monitored and recorded. The acquisition system of the universal testing machine recorded the load-displacement data at a constant cross-head speed of 5 mm/min [14]. Three samples were tested for each condition and good agreement between their results were obtained.

The load-displacement data and profile were used to assess the energy absorption [15]. Peak load P_i is usually indicated highest point before the post-crushing zone. The mean load P_m is the average load during the post crushing stage. The collapsible energy absorption devices must also provide a long deformation path to sufficiently and gradually reduce the deceleration of the protected occupants. Therefore, when evaluating the crashworthiness of an energy absorption device, great attention should be directed to its instantaneous crush force efficiency CFE, which is defined as the ratio between P_m and P_i. The energy absorbed E is the force value at each compression distance, which it evaluates

the area under load-displacement, and is defined as $E = \int P \, d\delta$. Finally, to access the amount of energy consumed by each unit mass, the specific energy absorbed (E_S) is used. Details on each parameter can be found in [10].

5. Results and Discussions
5.1. Load-displacement and crushing mechanism
The direct output of the machine is the load-displacement profile. As samples, the data obtained for the specimens at room temperature and at 120 ºC is shown in Figure 1. Good repeatability is shown in Figure 1, for the same condition. It is worth remarking that the same behavior is shown for the other three test conditions.
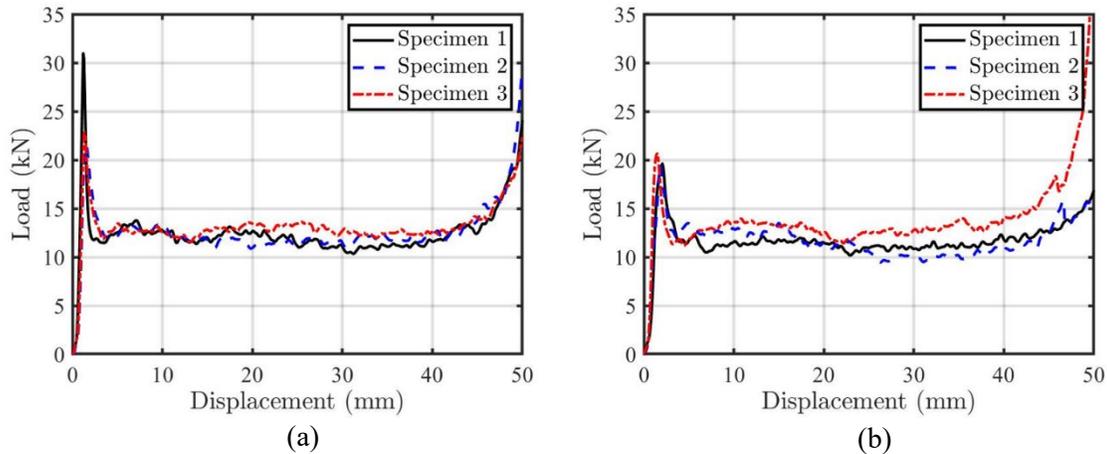

(a)　　　　　　　　　　　　　　　　　(b)

Fig.1: Load-displacement profile of the specimens (a) without thermal aging and (b) with thermal aging at 120 ºC. Three samples are shown for each condition.

The load-displacement profiles in Figure 1 are typical for composite tube subjected to axial crushing, see for example the results in [16]. The first stage is the pre-crushing stage. During this stage, the load-displacement relationship is linear, as it is clear in Figure 1. No visible damage is associated with this pre-crushing stage, Figure 2(i). The end of the first stage is the peak load, after which a drop in the load-carrying capacity of the specimen is recognized. After the peak load, the post-crushing stage starts. On the load-displacement profile, this stage is characterized by several peaks and valleys, with a small amplitude, which indicates a steady-state crushing. On the specimen, Figure 2(ii-vi), this stage is characterized by tearing, fragment, and folding damage. Several authors [17,18] studied the fractography during the post-crushing stage. They concluded that most of the known damage mechanisms (matrix cracking, fiber-matrix debonding, fiber micro buckling, delaminations, and fiber failure) are contributing to the composite tube behavior. This stage continues until the specimen's final densification (at which the specimen is not able to carry any extra load and the stiffness of the machine starts to contribute to the load-displacement profile). The images of the damage propagation and initiation do not show any dependency of the aging temperature. The image of the specimen after crushing shows that the outer layer (0º) experiences longitudinal splitting driven by matrix cracking, and then it is folded outside, Figure 2(vii). The other layers are crushing inward to fill in the internal hole of the tube.

5.2. Crashworthiness Assessment
Figure 3 shows the effect of the aging temperature on the load-displacement profile of the CFRP composite tubes. The data is considered for a maximum displacement of 50 mm, for ease comparing the energy absorbed at different temperatures. The load-displacement profile shown in Figure 3 is the mean of three specimens assessed by each condition. The data shows that the highest load-carrying capacity is recorded at RT, as well as at 150 ºC. During the post crushing stage, profiles are very similar. In more detail, the peak force P_i and the average crushing force P_m are shown in Figure 4. The highest peak

load is recorded at RT, which decreases by increasing the aging temperature up to 120 ºC. At 150 ºC, an increase in the peak load is recorded; another decrease follows that. Three different phenomena govern this fluctuation in the load-carrying capacity.
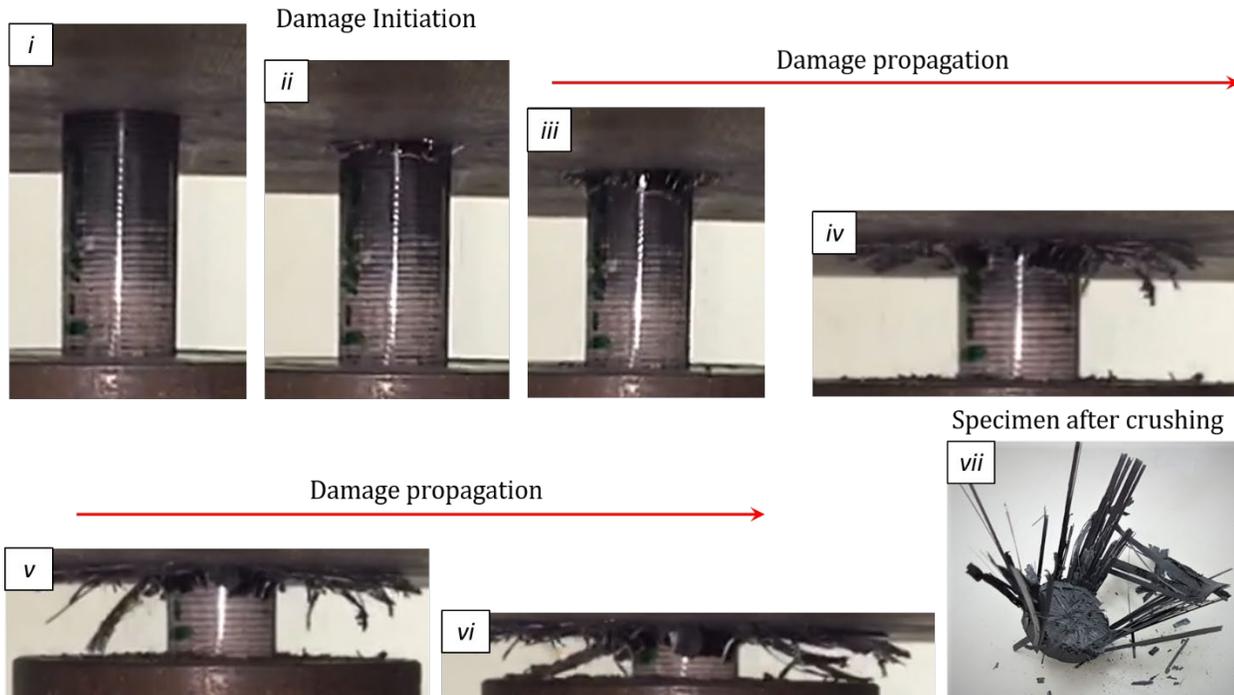

Fig. 2: Crushing mechanism of the CFRP composite tube.

For aging with temperatures much lower than T_g, thermal fatigue due to the mismatch of the thermal expansion coefficient between the carbon fibers and the epoxy matrix participates to the material degradation [19], which is the responsible of the first degradation in the P_i between RT and 120 ºC. For aging temperatures close but lower than T_g, the consolidation phase occurs due to the post-curing reaction that facilitates the adhesion between the fibers and the matrix, maintaining and improving the load-carrying capacity of the composite tube. Similar results were already reported by Garcia-Moreno [20] under impact and bending and by Shaoquan et al. [21] under impact loading. At aging temperatures above T_g, chemical aging mechanisms, which involve chain rupture, oxidation, and catalytic reaction of gases and pyrolization, occurred [5], which is the responsible of the second degradation in the peak load after 150 ºC.

On the other hand, the aging temperature does not show any impact on the average crushing load (the values shown in Figure 4 are the average of three samples). As a result, the crush force efficiency (CFE) increases by decreasing the peak load and vice versa, Table 2. Although it is improving by temperature up to 120 ºC, the CFE of the tubes under investigation is still low, compared to the optimal value of 100%. A woven layer on the surface and/or a filler may improve such a parameter, which is beyond the scope of the current study. Similar to the load-carrying capacity, the energy absorbed, Figure 5, and the specific energy absorbed, Table 2, are affected by the chemical changes during the thermal aging. The energy absorbed at room temperature is the highest recorded, which is followed by a reduction in the energy absorbed, up to 120 ºC. At 150 ºC, the energy absorbed increases due to the post-curing reaction before being decreased after the T_g. The reduction in the energy absorbed due to the thermal aging from RT to 120 ºC is 10%. On the normalized values (E_S), Table 2, the maximum reduction is 13.6%. Due to the post-curing process at 150 ºC, these composite tubes recover most of its original energy per unit mass (E_S).
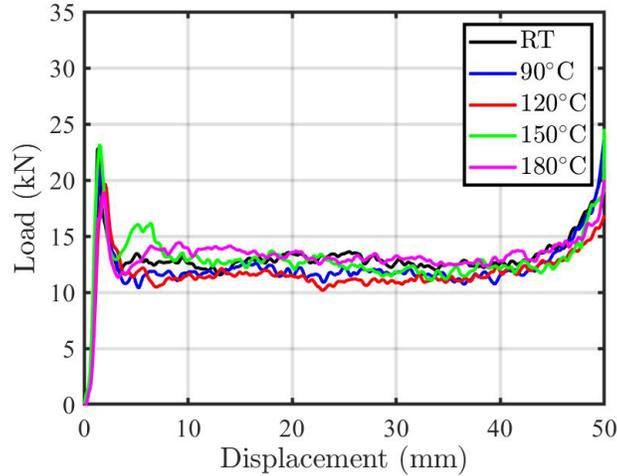
Fig. 3: Summary of the effect of the aging temperature on the load-displacement profile of the CFRP composite tubes.

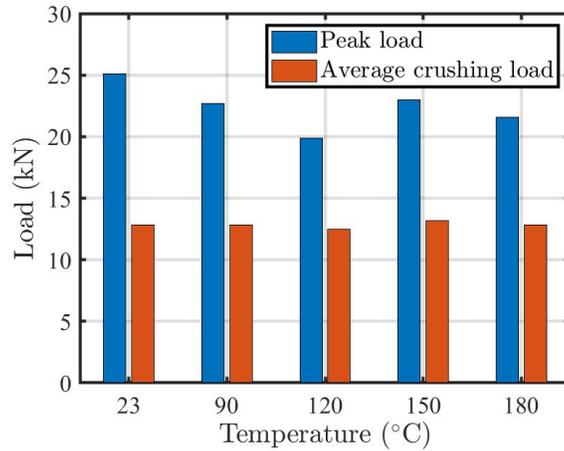Fig. 4: Peak and average crushing force as functions of the aging temperature.

Table 2: Crush force efficiency CFE and the specific energy absorbed Es of the test campaign at different aging temperature. (CoV is the coefficient of variation of the measurements at each aging temperature)

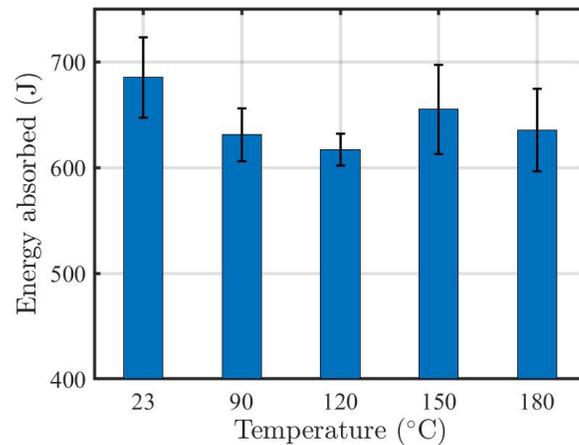| Temperature (ºC)	Crush force efficiency		Specific energy	
	CFE (%)	CoV (%)	E_S	CoV (%)
23	52.6	10.1	80.7	8.34
90	57.1	8.14	72.2	8.83
120	62.8	3.74	69.7	15.9
150	58.6	8.31	50.5	1.34
180	61.5	14.1	78.4	4.40

Fig. 5: Energy absorbed E as functions of the aging temperature

In real structure applications, composite tubes can be exposed to air at -73 ºC to 80 ºC in aerospace whereas, it is exposed to -140 ºC to 120 ºC in space applications [22]. In automotive, the temperature around the engine and exhaust can exceed the 200 ºC [23]. For light weighting, transportation applications use polymeric fiber-reinforced composites for their structures, with an extra advantage of its crashworthiness. The results obtained in the current study recommended that 10-15% design margins need to be considered while designing FRP composites to compensate for the temperature aging in real working environment.

6. Conclusion

The current paper pretested an experimental study to investigate the effect of thermal aging on the crashworthiness parameters of cylindrical CFRP tubes. The specimens were tested under compression after thermal aging at 90ºC, 120ºC, 150ºC, and 180ºC, in addition to tests at room temperature. The peak and average crushing forces, the crush force efficiency, the energy absorbed, and the specific energy were used to assess the composite tubes' crashworthiness.

The results did not show any dependency of the load-displacement profile neither the apparent crushing mechanism on the applied thermal aging. On the other hand, the peak force, the energy, and the specific energy showed degradation by increasing the temperature up to 120 ºC, controlled by the matrix cracking and debonding due to thermal mismatch between the fiber and matrix and matrix degradation. At 150 ºC, the crashworthiness improved, as a result of the post-curing process of the matrix. At a temperature higher than the T_g (at 180 ºC), the crashworthiness parameters decreased as a result of the chain rupture, oxidation, and catalytic reaction of the matrix.

Acknowledgements

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