

1 **Chapter 12:**
2 **Treatment effect on failure mode of industrial carbon textile at elevated**
3 **temperature**

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10 **Abstract**

11 Industrial textiles are manufactured in factory as commercial products for diverse
12 application in industry (automotive engineering, civil engineering, transportation and
13 energy, etc) thanks to their good mechanical properties in some special cases of loading.
14 In case of fire or at elevated temperatures, changes of textile properties are considered
15 as an important factor for the application of textiles. The fibre treatment by different
16 products in nature is a factor for the changes of textile properties with elevated
17 temperatures. This book chapter presents an experimental study on the
18 thermomechanical tensile behaviour of three different industrial carbon textiles at
19 elevated temperatures ranging from 25 °C to 600 °C. Three industrial carbon textiles
20 were treated in manufacturing chain with different products in nature as coating (epoxy
21 resin with different ratios and amorphous silica). By comparing the results obtained on
22 three carbon textiles, the effect of fibre treatment on the thermomechanical behaviour
23 (mechanical properties and property evolution depending on elevated temperatures) of

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carbon textile was found. The failure mode analysis was investigated by observing all carbon textile specimens after thermomechanical tests to understand the effect of fibre treatment on failure mode of carbon textile at elevated temperatures.

Keywords

Industrial carbon textile, textile treatment, elevated temperature, stress–strain curve.

1. Introduction

Over the past some decades, the industrial textiles in different nature were widely fabricated in factory as a commercial product thanks to their diverse applications in automotive engineering, civil engineering, transportation and energy, medical purposes, etc [1-8]. The industrial textile has been considered as an alternative material to contribute in the industry development of the world. The textile in combination with polymer matrix or cement matrix gives a new material [Fibre Reinforced Polymer (FRP) or Textile Reinforced Concrete (TRC)], that has better characteristics (high strength and stiffness, slight, etc) than other traditional material [4-13]. They were also successfully used in some special cases of loading or environment such as thermal shock, seismic, contact, corrosion, etc [4-7, 14-16]. However, in case of fire or at high temperature, changes of textile properties are considered as an important factor for the application of textiles. So, it needs more experimental studies on the industrial textile behaviour under or after exposure to elevated temperatures.

In the literature, some fire tests have been carried out on specimens with presence of textile composite to find its reinforcement capacity in fire [17-20]. Several studies have been conducted on the tensile behaviour of industrial textile or textile composite specimens after exposure to elevated temperatures (called residual condition). These studies aimed to identify their tensile residual behaviour with elevated temperatures [21-27]. The residual behaviours of basalt textile and basalt textile – reinforced concrete

composite specimens after exposure to 1 h at elevated temperatures from 25 °C to 1000 °C were presented in [25-26]. The effect of thickness and reinforcement configuration on flexural and impact behaviour of glass textile-reinforced polymer composite was investigated in [27] after exposure to four levels of elevated temperatures 60 °C, 120 °C, 200 °C and 300 °C. Some experimental research have been performed on industrial textile or textile composite specimens under simultaneous actions of temperature and mechanical loadings (called thermomechanical condition) [13, 28-30]. These tests aimed to identify the tensile behaviour and thermomechanical properties of studied materials at different temperatures. Nguyen et al [13] has performed experimental and analytical investigation of elevated temperature behaviour on carbon textile-reinforced polymer (FRP) specimens in two thermomechanical conditions: thermomechanical test at constant temperature (TMCT) and thermomechanical test at constant load (TMCL). Homoro et al [30] recently studied experimentally and analytically thermomechanical behaviour of alkali-resistant (AR) glass textile and discontinuous short AR glass fibres -reinforced concrete (TRC) at temperatures ranging from 25 °C to 600 °C. Few research was performed on carbon textile reinforced mortar (TRM) in comparison with fibre reinforced polymer (FRP) as strengthening materials of structure specimen at elevated temperatures to characterize the shear, bond and flexure behaviour [31-33]. As the results obtained in the literature, a notice could be concluded that the elevated temperature behaviour of industrial textile and its composite material depended on several factors such as fibre nature, matrix nature and reinforcement ratio in composite material, the fibre treatment by different products. Among these factors, the product of textile treatment greatly influenced to the failure mode of industrial textile and its composite material specimens at different temperatures.

73 As regards to the failure mode of industrial textile, in the literature, there were some
74 studies conducted to the failure mode of industrial textile under action of mechanical
75 load and elevated temperatures [12-13, 25-26]. Zhai et al [12] have performed an
76 experimental investigation on longitudinal tensile specimens of glass textile treated
77 with polypropylene resin at room and different temperatures. The results showed that
78 the temperature effect on polypropylene resin treatment influenced to the failure mode
79 of specimens. As regards to the failure mode of the specimens tested at 23 °C, 50 °C
80 and 70 °C, Zhai et al [12] displayed the brittle failure mode with the pull-out of the
81 monofilaments. At 90 °C, the longitudinal splitting of the filament groups is caused by
82 the weakness of interface between fibres and resin treatment product. In this research,
83 the optical microscopy image method was used to observe the failure mode of glass
84 textile specimens at micro scale. As results of the optical microscopy image method in
85 [12], it showed the extensive debonding in fibre groups along the longitudinal direction
86 of specimens.

87 In their study, Rambo et al [21, 25-26] have been conducted the studies on the elevated
88 temperature behaviour of basalt textile and basalt TRC composite specimens. As results
89 obtained, basalt textile specimens after exposure to elevated temperatures provided a
90 linear behaviour with a fragile rupture mode. This failure mode was characterised by
91 the drop in stress of “stress – strain” curves of basalt textile specimens. As regards to
92 the effect of textile treatment, it can be seen that a coating of styrene-acrylic latex had
93 a positive effect to improve the mechanical properties (tensile strength and Young’s
94 modulus) of specimens in the temperatures ranging from 75 °C to 150 °C. After cooling,
95 the textile pre-impregnation by coated polymer improved the uniform stress distribution
96 between the filaments in textile yarns. In basalt TRC composite specimen, the heating
97 - cooling regime of residual test at temperature from 75 °C to 150 °C positively affected

to this resin treatment of basalt textile to improve the composite performances (tensile strength and Young's modulus). As regards to the failure mode of basalt textile, scanning electron microscopy (SEM) method was used to observe the damage processes in the basalt textile after exposure to different temperatures. As results, the basalt textile provided a fragile rupture mode which was caused by the minor crack-bridging action of the filaments or the melting of filaments at elevated temperatures.

In the recent study of Nguyen et al [13], carbon textile was manually treated with two-component epoxy resin as a matrix in laboratory condition. It provided a brittle failure mode under simultaneous thermal and mechanical loadings at different temperature levels. This failure mode was also outline by a drop in stress of "stress – strain" curves at different temperatures. By observing the carbon textile specimens after thermomechanical tests, it could be divided this failure mode by four types of specimen failure. The first failure type was remarked by the damage of both carbon textile and coated epoxy for specimens at room temperature, whereas at 200 °C, the coated resin melting was caused to the debonding of the filament groups (the second failure type). The complete melting and a partial decomposition of the coated resin at 400 °C leaded the filament breakage at different section (the third failure type), whereas the complete burning of coated resin and the oxidation of a part carbon fibre at 600 °C were notable (the fourth failure type).

To the best of the authors' knowledge, no results are available concerning the thermomechanical test carried out on the specimens of continuous carbon textile, which has been industrially treated in factory by different products in nature. There are also no results regarding effect of textile treatment on the thermomechanical behaviour and failure mode of carbon textile at elevated temperature. The aim of this work is to contribute in answering the question: What is effect of textile treatment on the

thermomechanical behaviour and failure mode of industrial carbon textile? This work also provides the scientific community with experimental data concerning the thermomechanical behaviour of industrial carbon textiles.

This chapter presents an experimental study on the tensile behaviour of three different industrial carbon textiles subjected to simultaneous mechanical and elevated temperature loadings. Three continuous carbon textiles, which were industrially treated with different products in nature and as commercial products, were tested at different temperature levels varying from 25 °C to 600 °C. The results on three carbon textiles were compared to find the effect of fibre treatment on the thermomechanical behaviour and failure mode of carbon textile. In the following sections of this chapter, experimental work including the use of equipment, test specimens and loading paths are presented in section 2. The experimental results are presented in section 3, and then analysed and discussed in section 4. This chapter ends with a presentation of main conclusions and future works.

2. Experimental work

This section presents the equipment used and loading paths for characterization of residual and thermomechanical behaviour of carbon textile.

2.1. Equipment used

The test machine, furnace and laser sensor were used in this research in order to generate the simultaneous actions of elevated temperature and mechanical loading to specimen, and to measure the thermomechanical strain of carbon textile specimen.

2.1.1. Test machine

The test machine used in this research, TM20kN-1200°C, can generate a maximal force up to 20kN for the direct traction test. The traction loading is controlled by the vertical displacement of traverse thanks to a control programme (Test Expert II software) in the

computer of the control system for the test setup. The increasing rate of the force depends on the type of material (ultimate strength and stiffness). During the test, the data including mechanical load and traverse movement of the test machine, are recorded at least twice per second and can then be exported in the form of datasheets for results analysis. Figure 16.1 shows the universal tensile machine with other equipment for thermomechanical test.

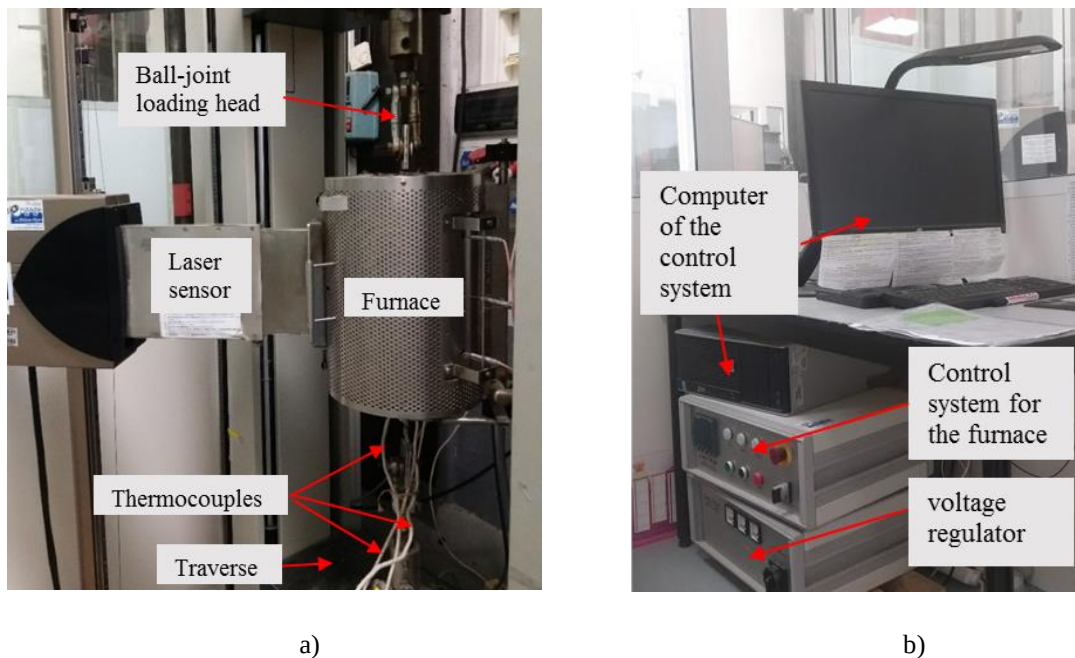


Fig 12.1 Universal traction machine, TM20kN-1200°C (a): Overview of the test setup; (b) Control system for test setup.

2.1.2. Furnace

The test machine is equipped with a small cylindrical furnace with 3 dimensions like that: height of 40 cm, an internal diameter of 10 cm, and an external diameter of 27.5 cm. This furnace can generate, in the same time with mechanical loading during the test, temperature loadings of specimens potentially up to 1200 °C with the maximum heating rate of 30 °C/min. The temperatures in the furnace are determined by integrated thermocouples and also controlled by the test programme. With the equipment of furnace, the test machine can make it possible to apply simultaneous tensile mechanical

and elevated temperature loadings on a sample. Figure 16.2 shows the detail of the furnace installed on the test machine.

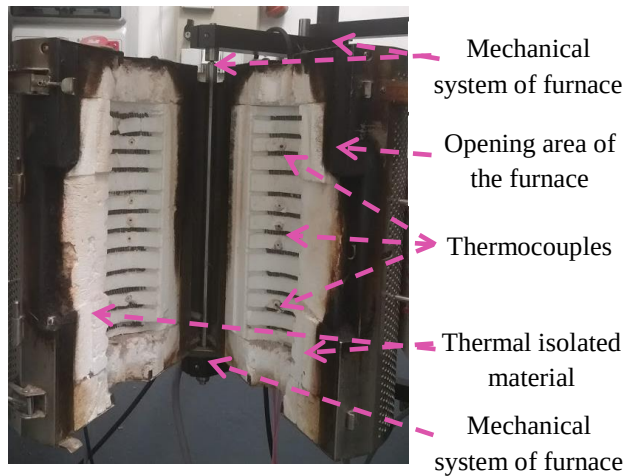


Fig 12.2: Detail of the furnace for thermomechanical test

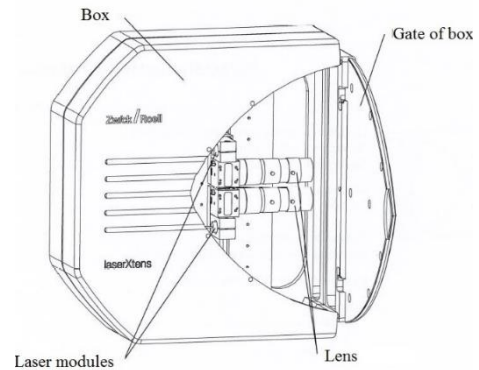


Fig 12.3: Laser sensor details for the measurement of specimen axial strain

2.1.3. Laser sensor

In this research, non-contact measurement method of laser sensor was used to measure the thermomechanical strain of test specimens. The measurement principle of this method is explained by the description of the laser sensor system. The measuring system consists of two CCD (Charge Coupled Device) cameras with one lighting unit for each one and a linear motor for continuous adjustment of the spacing between both cameras. The cameras are vertically arranged, and in parallel view with the specimen in the horizontal direction. By using the motorized camera setting, it can be set different reference lengths for measuring axial strain of specimen. The illumination is produced by a laser diode with a diverging lens upstream. The lens sweeps the light beam and thus creates on the test surface a lighting mark extended in the vertical direction whose dimensions roughly correspond to the visual field of the camera. The camera image is digitally recorded by the control computer. The image processing software exploits the movements of the images and derives values of axial strain of specimen (see Fig 16.3).

The existence of a small furnace to generate the temperature action around the test specimen is one of the difficulties for a method of measuring contact. Moreover, the thinness of the test specimen of carbon textile can create difficulty in the specimen axial strain measurement with contact measurement methods. In particular, the elevated temperature in the furnace greatly influences the results of other strain measurement instruments in the contact measurement method. With the non-contact measurement method by the laser sensor, it provides a relative displacement between two laser bobbins on the carbon textile specimen (Figure 16.3). The axial strain of the carbon textile specimen is calculated as the ratio of the relative displacement of two laser bobbins and their initial distance. When the tested material is homogeneous, as carbon textile, the measurement of the laser sensor can provide the axial strain for the part of the specimen placed in the furnace during the thermomechanical test. This method of measurement has been used, developed, and validated in previous works and has given good results for different composite materials [13, 28-30].

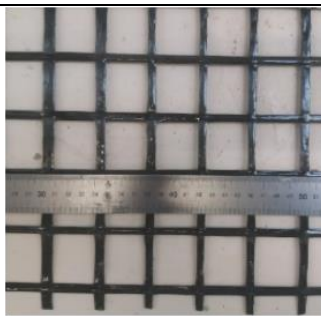
2.2. Specimens

The materials used in this research are three continuous carbon textiles which are called GC1, GC2, and GC3 textile. They were manufactured in a factory as industrial products for multi applications. They have good thermal and mechanical characteristics: very high tensile strength and modulus, non-corrosion, low mass per unit area, simple and flexible application, etc. Three carbon textiles were coated with different treatment products in nature. The GC1 and GC3 textiles were pre-impregnated by epoxy resin with two different pre-impregnation ratios, completely pre-impregnated for the GC1 textile and a very low level for GC3 textile, whereas the GC2 textile was treated with a product of amorphous silica as a coating. They were also manufactured in grid form

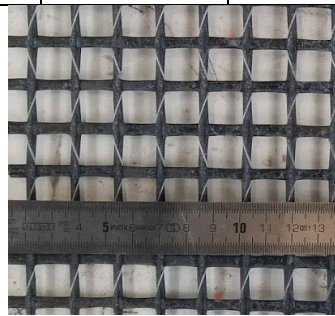
with different grid geometries (see Fig 12.4). The properties of the three studied carbon textiles are summarized in Table 12.1.

Table 12.1: Properties of three studied carbon textiles

Properties	GC1	GC2	GC3
Density (g/cm ³)	3.43	1.79	1.89
Grid geometry (longitudinal × transverse spacing) (mm × mm)	46 × 41	17 × 17	33 × 33
Type of coating	epoxy resin	amorphous silica	epoxy resin
Cross-sectional area of one individual strand	1.85 mm ²	1.795 mm ²	1.80 mm ²



(a) GC1 carbon textile



(b) GC2 carbon textile



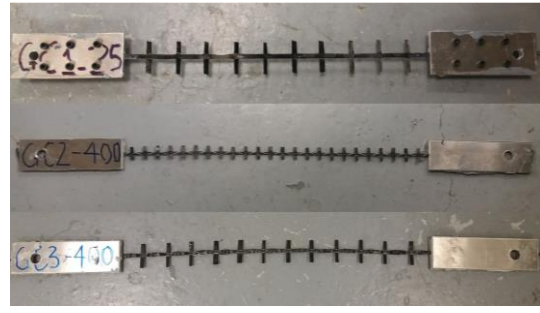
(c) GC3 carbon textile

Fig 12.4: Images of three carbon textiles (GC1, GC2, GC3) used in the experimental study

The test specimens in this experimental study were prepared by hand in the laboratory. Firstly, a longitudinal yarn (the warp) of the textile was cut to obtain carbon textile samples of 750 mm in length. After that, two ends of the specimens were bonded with aluminium plates for good transmission of the mechanical force to the textile specimens. Finally, the specimens were embraced at room temperature for 7 days, then referenced and ready for the tests at different temperatures (see Fig 12.5). There were 42 tests carried out on the specimens of three carbon textiles at different temperature levels varying from 25 °C to 600 °C. Table 16.2 shows the list of the specimens and the tests carried out in this research.



(a) Embracing for specimens



(b) Carbon textile samples ready for test

Fig 12.5: Preparation of samples

Table 12.2: List of tests conducted on the specimens of three carbon textiles

Designation of the specimen	Dimensions of the specimen [cross section, S (mm^2) length, l (mm)]	Temperature ($^{\circ}\text{C}$)	Exposure duration	Number of tests
GC1-T-a,b,c	$S = 1.85$ (mm^2); $l = 425$ (mm)	$T=25, 200, 400, 500, 600$	1 h	14
GC2-T-a,b,c	$S = 1.795$ (mm^2); $l = 420$ (mm)	$T=25, 200, 400, 500, 600$	1 h	14
GC3-T-a,b,c	$S = 1.80$ (mm^2); $l = 425$ (mm)	$T=25, 200, 400, 500, 600$	1 h	14
Total of tests				42

2.3. Loading paths

The textile specimen was tested in the thermomechanical condition at constant temperature (TMCT) to identify the thermomechanical behaviour of three carbon textiles. The TMCT loading path consists of three phases as described in previous works [13, 28-30, 34]. The first test phase consists of increasing the temperature around sample to the desired temperature level. The rate of temperature increase varies from 6 $^{\circ}\text{C}/\text{min}$ to 20 $^{\circ}\text{C}/\text{min}$ depending on the target temperature (from 200 $^{\circ}\text{C}$ to 600 $^{\circ}\text{C}$) of the test. The second test phase consists of maintaining the target temperature (T_{target}) for a period of 1 h in order to homogenize the temperature around specimen. The third test phase consists of applying the quasi-static tensile load monotonically to specimen until

failure, the laser sensor is activated during this phase to measure the axial strain of sample (see Fig 12.6).

The stress of specimen corresponding to the failure point is quantified as the ultimate stress (σ_{UTS}). The axial strain of specimen corresponding to failure point is quantified as the maximum axial thermomechanical deformation ($\epsilon_{TM,UTS}$). Figure 12.6 shows the thermomechanical test procedure on the test specimens of carbon textiles with three phases. After the test, all data, including temperatures, mechanical load, and specimen axial thermomechanical strain or traverse movement, are recorded at least twice per second and can then be exported in the form of datasheets for results analysis.

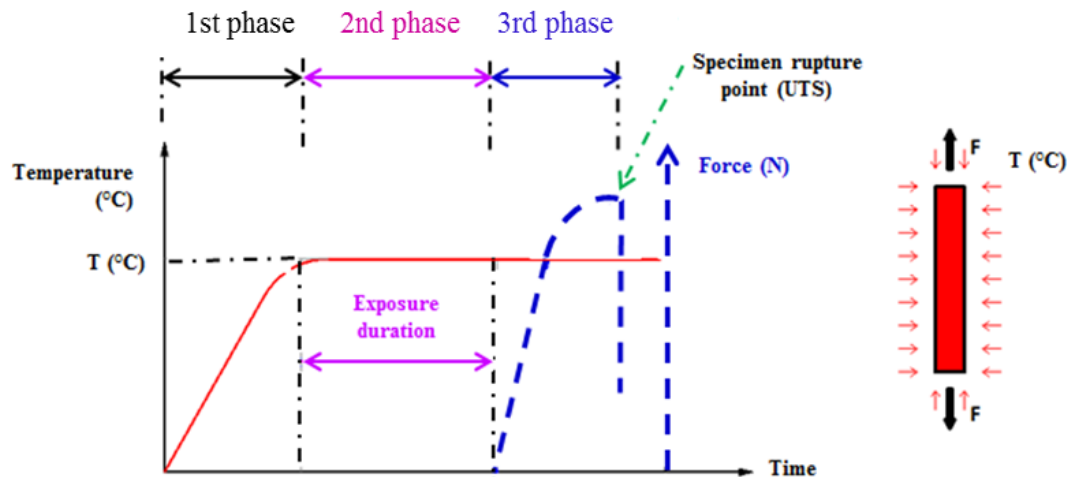


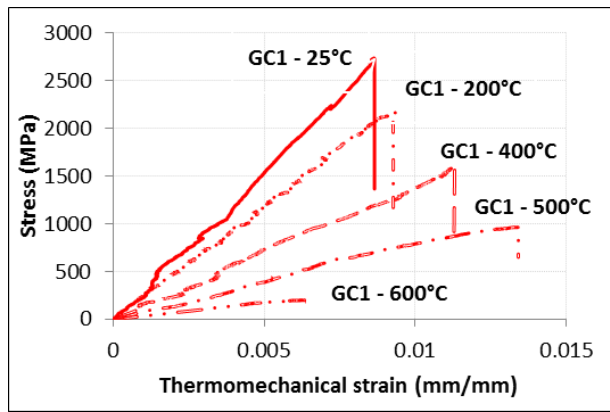
Fig 16.6: Loading path of thermomechanical tests carried out on specimens of three carbon textiles

3. Results

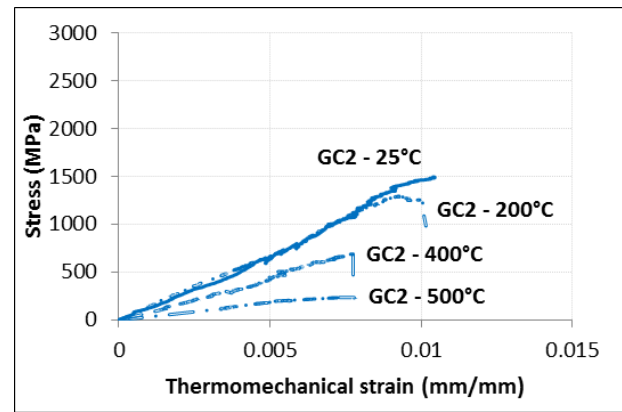
This section presents the results of thermomechanical tensile tests performed on carbon textile specimen in comparison with other results of previous works in the literature.

3.1. Elevated temperature behaviour of industrial textiles

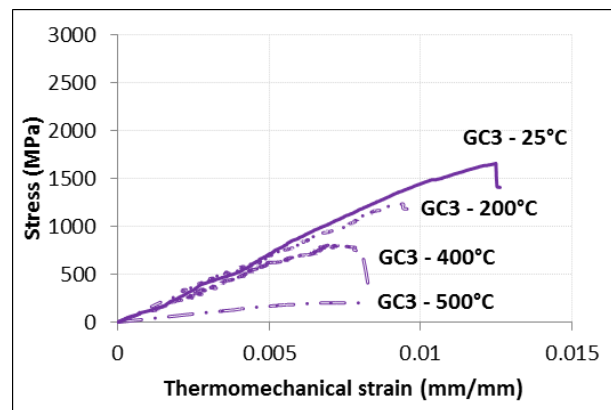
Figures 12.7(a,b,c) shows the “stress–thermomechanical strain” curves of three carbon textile samples (GC1: Figure 16.7a; GC2: Figure 16.7b; GC3: Figure 16.7c) at different temperatures ranging from 25 °C to 600 °C.



(a) GC1



(b) GC2



(c) GC3

Fig 12.7: Thermomechanical behaviour of three carbon textile: stress–thermomechanical strain relationship at different temperatures

Figures 12.7a,b,c show only one average ‘stress/strain’ curve for each test temperature so that the curves can be legible for all temperature levels varying from 20°C to 500°C for each carbon textile.. From Figure 12.7, it could be seen that all carbon textile samples exposed to 1 h at elevated temperatures gave an almost linear behaviour up to the test specimen failure. The “stress–thermomechanical strain” curves of both GC2 (Figure 12.7b) and GC3 (Figure 12.7c) carbon textiles were similar at each temperature level, while the initial slope (stiffness) of the stress-strain curve of the GC1 carbon textile was higher about 2 times than that of GC2 and GC3 in the same temperature level.

The ultimate strength of three carbon textiles at 25 °C is 2616 MPa, 1311 MPa and 1443 MPa (on average), respectively for GC1, GC2 and GC3 carbon textile. With increasing of temperature, this values decreases progressively into a negligible value at 600 °C. The GC1 carbon textile gave an ultimate strength of 205 MPa (on average) corresponding to a 92.8% reduction of this value at ambient temperature, whereas two other textile specimens (GC2 and GC3 textiles) have been broken before the thirsh phase of test. That's why there were not available results for thermomechanical tests of GC2 and GC3 carbon textiles. Table 16.3 presents the other average ultimate strength values of thermomechanical tests on the specimens of three carbon textiles at different temperature levels varying from 25 °C to 600 °C. In Table 12.3, it could be also found the standard deviation values of the mechanical properties of three carbon textiles at different temperatures.

As regard to the Young's modulus of three carbon textiles, it can be seen in Figure 12.7 that the temperature action also influenced on the initial slope of the "stress–thermomechanical strain" curves of three carbon textiles. So, the stiffness of three carbon textiles decreases progressively when the temperature increases. Young's modulus of three carbon textiles was determined by two points corresponding to the deformation of 0.05% and 0.25% of "stress–thermomechanical strain" curve. At room temperature, Young's modulus of three carbon textiles was 256 GPa, 144 GPa and 130 GPa (on average), respectively for GC1, GC2 and GC3 carbon textiles. At the temperature of 600 °C, the thermomechanical test gave a very low Young's modulus value of 29 GPa (on average) for GC1 carbon textile, and non-value for two others. Table 16.3 shows all average values of thermomechanical test concerning the Young's modulus of three carbon textiles.

Table 12.3: Results of the direct tensile tests performed on three carbon textile specimens (the standard deviation values are written in parallel)

Temperature (°C)	Heating rate (°C/min)	GC1 textile		GC2 textile		GC2 textile	
		Ultimate stress (MPa)	Young's modulus (GPa)	Ultimate stress (MPa)	Young's modulus (GPa)	Ultimate stress (MPa)	Young's modulus (GPa)
25	0	2616.6 (124.9)	256.2 (39.7)	1311.5 (158.3)	143.8 (7.2)	1442.7 (242.2)	130.2 (7.1)
200	6.67	2169.5 (175.5)	201.6 (29.0)	1152.5 (204.9)	138.6 (14.0)	1168.1 (103.0)	117.4 (25.4)
400	13.33	1652.2 (40.5)	138.8 (23.4)	708.8 (71.8)	107.1 (18.6)	845.9 (89.1)	95.9 (21.6)
500	16.67	795.7 (145.4)	77.6 (4.5)	308.1 (67.8)	39.7 (9.5)	185.7 (18.6)	38.4 (6.4)
600	200	204.9	29.5	-	-	-	-

3.2. Evolution of the thermomechanical properties as a function of temperature

As results presented in section 3.1, the mechanical properties of three carbon textile varied as a function of elevated temperatures. So, it could be defined the normalized mechanical properties (normalized ultimate stress and Young's modulus) for mechanical property evolution depending on the temperature. This value is determined by the ratio between the mechanical property at a temperature (T) and that at room temperature (σ_T/σ_{25} or E_T/E_{25}). The normalized mechanical properties of three carbon textiles are presented in Table 12.4. From Table 12.4, it can be seen that three carbon textiles gave the similar reductions of the normalized ultimate stress values when the

temperature increases from 25 °C to 400 °C. The normalized ultimate stresses were 82.9%, 87.9% or 81.0%, respectively for three carbon textiles at 200 °C, and were 63.1%, 54.0%, and 58.6% respectively for three carbon textiles at 400°C. At the temperatures above 400 °C, the GC1 textile remained more mechanical capacities than the other two textiles (GC2 and GC3). This carbon textile sustained 32.5% and 7.8% of its ultimate stress value at room temperature, respectively for 500 °C and 600 °C, whereas the other two textiles had an ultimate stress less than 22% and 0% compared with the ambient temperature value, respectively for 500 °C and 600 °C. Figure 12.8 shows the evolution of the normalized ultimate stress of three carbon textiles as a function of temperature.

Table 12.4: Evolution of the normalized mechanical properties of three carbon textiles as a function of temperature

T °C	Normalized ultimate stress			Normalized Young's modulus		
	σ_T/σ_{25} (%)			E_T/E_{25} (%)		
	GC1	GC2	GC3	GC1	GC2	GC3
25	100	100	100	100	100	100
200	82.9	87.9	81.0	78.7	96.4	90.1
400	63.1	54.0	58.6	54.2	74.4	73.6
500	30.4	21.1	12.9	30.3	23.8	29.5
600	7.8	0	0	11.5	0	0

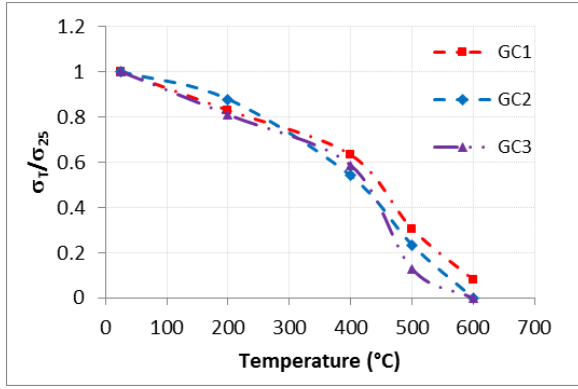


Fig 12.8 : Evolution of normalized ultimate stress obtained for the studied carbon textiles

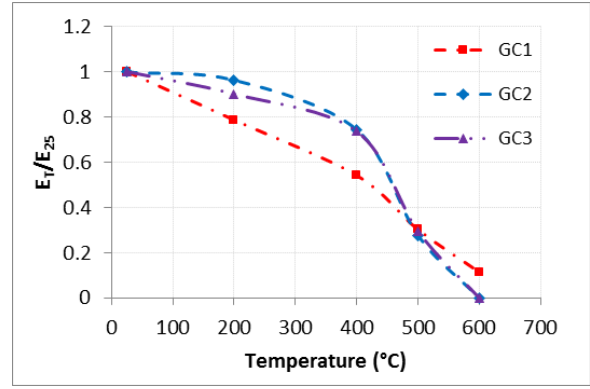


Fig 16.9 : Evolution of normalized Young's modulus obtained for the studied carbon textiles

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310 From Figure 12.8, the ultimate stress evolution of the GC1 and GC3 carbon textiles can
 311 be divided into two zones. At temperatures ranging from 25 °C to 400 °C, the ultimate
 312 stress slightly decreased as a function of temperature, about 20% at 200 °C and 40% at
 313 400 °C. At temperatures ranging from 400 °C to 600 °C, an important reduction of
 314 ultimate stress could be found. The complete decomposition of pre-impregnated
 315 products by epoxy resin in carbon textiles caused this considerable reduction. Figure
 316 16.9 presents the evolution of the normalized Young's modulus of three carbon textiles
 317 as a function of temperature. From Figure 12.9, it can be seen that GC2 and GC3 carbon
 318 textiles had almost the same Young's modulus evolution as a function of elevated
 319 temperatures. The normalized Young's modulus values were 96.4% and 90.1% at 200
 320 °C, 74.4% and 73.6% at 400 °C, 23.8% and 29.5% at 500 °C, respectively for GC2 and
 321 GC3 carbon textiles. From Figure 12.9, it can be seen that the influence of temperature
 322 on Young's modulus of the GC2 and GC3 carbon textiles could be divided into two
 323 temperature intervals. The first interval, from 25 °C to 400 °C, was described by a slight
 324 reduction of Young's modulus (about 25% at 400 °C). In the second interval, from 400
 325 °C to 600 °C, Young's modulus greatly decreased and was almost negligible at 600 °C.
 326 Whereas, Young's modulus of GC1 carbon textile progressively decreased and retained

78.7%, 54.2%, 30.3%, and 11.5% of its value at room temperature, respectively for 200 °C, 400 °C, 500 °C, and 600 °C.

3.3. Discussion

This section presents discussions to explain the effect of carbon fibre treatment products on the results obtained (ultimate strength and Young's modulus, thermomechanical property evolution depending on temperature, and failure modes of textile specimens), which were presented in section 3.

3.3.1. Effect of textile treatment on the elevated temperature behaviour of carbon textiles

As result presented in section 3.1, it could be found the influence of treatment by different products on the behaviour of three carbon textiles at elevated temperatures. Three studied carbon textiles gave the different values of ultimate stress and Young's modulus in the same temperature level even if they have almost equivalent cross-sections for a textile yarn.

The GC1 carbon textile has an important mechanical capacity and is better than two other carbon textiles (GC2, GC3) thanks to its very good pre-impregnation with an epoxy resin product (see Fig 12.10a). This treatment par epoxy resin gave a good load transmission between the monofilaments of textile yarn which has assured the working in common between the monofilaments. The ultimate stress of the GC1 textile was higher about 2 times than this value of the other two textiles at different temperatures (see Fig 12.10a). At the temperature above 400 °C, although epoxy resin treatment has begun to be partially decomposed and burned, but it still assured the load transmission between the monofilaments of GC1 textile yarn. As regards to the treatment of two other textiles, the amorphous silica for GC2 carbon textile and the epoxy resin with very low content for GC3 had the similar effect on loading capacity of textile. This little

bonding between the monofilaments within GC2 (or GC3) caused less carrying load of
 a textile yarn of GC2 (or GC3) than that of the GC1 carbon textile. As results of
 Young's modulus at elevated temperatures, it could be also found the effect of the pre-
 impregnated product on stiffness of three carbon textiles. The perfect pre-impregnation
 of an epoxy resin product for GC1 carbon textile has leaded a good relationship between
 the mono-filaments of textile yarn. So, they have worked together in the longitudinal
 direction to support the tensile loading. This leaded a higher stiffness value of GC1
 compared to those of two others textiles (GC2 and GC3). The coating treatment of the
 GC2 and GC3 textiles also gave the same effect on stiffness capacity at different
 temperatures. As experimental results, the Young's modulus of two carbon textiles
 (GC2 and GC3) was approximately similar, while this value of GC1 carbon textile was
 greater about 1.5 times than that of two other carbon textiles (see Fig 12.10b).

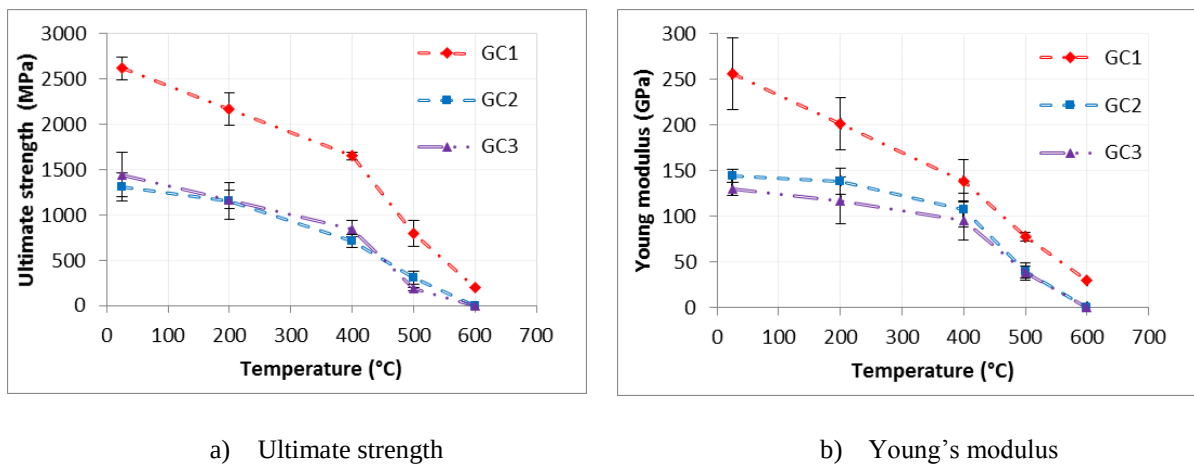


Fig 16.10: Evolution of mechanical properties of three carbon textiles with elevated temperatures;

Concerning the mechanical property evolution as a function of temperature, the
 experimental results showed that the thermomechanical properties of three carbon
 textiles differently decrease for each studied carbon textile when the temperature
 increases. The evolution of the ultimate stress and/or Young's modulus depended on
 the treatment product and the pre-impregnation ratio of the carbon textiles. As regards

to the reduction of the ultimate stress, the carbon textiles treated with the resin product (GC1 and GC3) gave a typical evolution depending on the temperature. There are two intervals of this evolution: a slight reduction (approximately 40%) in the temperature ranging from 25 °C to 400 °C and a significant decrease at temperatures from 400 °C to 600 °C. In the first interval, the normalized ultimate stress of two carbon textiles (GC1 and GC3) was approximately similar as presented in section 3.1. It means that significant contribution of the impregnated resin has still ensured good charge transmission between monofilaments when this treatment product has not yet started to decompose or burn at the temperature from 25 °C to 400 °C. In the second interval, the textile perfectly pre-impregnated in the epoxy resin (GC1 textile) could remain very well its ultimate stress compared with the value at room temperature, while the other one (GC3 textile) had very low value of normalized ultimate stress. It means that the impregnated ratio significantly influenced on the evolution of the ultimate stress at the temperature above 400 °C. As regards to the ultimate stress evolution of the GC2 carbon textile, the treatment by an amorphous silica product has led a curved progressive decrease with the increasing of the temperature. The elevated temperatures have not significantly influenced on this treatment product for a physical or chemical transformation in GC2 carbon textile. This treatment product aims to improve the bond between the carbon textile and the matrix in composite material.

Concerning the Young's modulus evolution of three carbon textiles as a function of the temperature, it could be found that, this evolution of the GC2 and GC3 textile was similar with two intervals: the first interval of a slight reduction (approximately 25%) in the temperatures ranging from 25 °C to 400 °C and the second from a very significant decrease to a negligible value at 600 °C. It means that the treatment products by amorphous silica for GC2 textile and epoxy resin with very low ratio for GC3 textile

had the similar contribution to their stiffness at elevated temperatures. At moderate temperatures from 25 °C to 400 °C, there was some contribution of the impregnated epoxy resin to GC3 carbon textile stiffness. So, it has made a small difference between the normalized Young's modulus values of two textiles (76.4% for GC2 and 73.6% for GC3). At the temperatures above 400 °C, there was complete decomposition of the impregnated epoxy resin, which caused no more contribution of this treatment product to GC3 carbon textile stiffness like that of amorphous silica product in GC2 carbon textile. As regards to the stiffness of GC1 carbon textile, the impregnated resin contribution in a textile yarn caused a progressive reduction of Young's modulus as shown in Figure 12.10b. The effect of temperature on the resin matrix significantly influenced Young's modulus of the GC1 carbon textile. At a moderate temperature (from 25 °C to 400 °C), the impregnated resin was gradually softened, which caused a lesser contribution to carbon textile stiffness. At the temperatures above 400 °C, the GC1 carbon textile was gradually decomposed and burned until its complete decomposition, which largely influenced the working in common between carbon monofilaments.

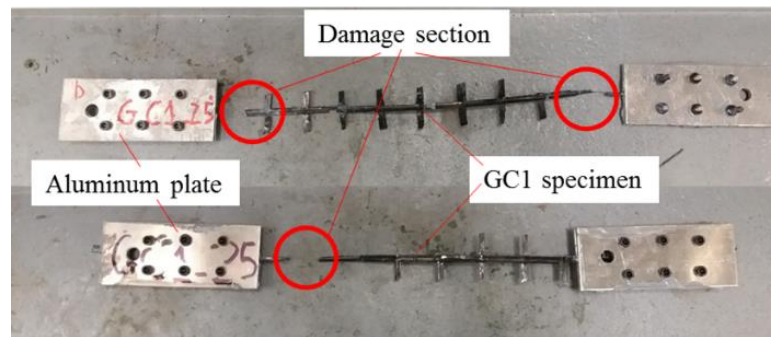
3.3.2. Failure modes

The failure modes of carbon textile are presented by observing the specimens after the tests at different temperatures in this section. The results revealed two main failure modes for the three carbon textiles: a brittle failure mode marked by a drop in stress on the “stress–thermomechanical strain” curve, and a progressive failure featured by a stress progressively decreases as a function of the deformation on the “stress–thermomechanical strain” curve. This argument is consistent with the results available in the literature [35].

At room temperature, the failure mode of three carbon textiles was similar like that of carbon fibre. The specimens were broken in an abrupt way which is called fragile rupture mode when the material reached a limited state. Thanks to the textile treatment by an epoxy resin product, there was a good load transmission between the monofilaments of GC1 and GC3 carbon textile yarn (in particular GC1 textile). So, the test specimens were completely broken by the monofilaments damage in the same time on the weakest section of textile yarn. It means that the rupture energy was suddenly liberated by the breakage of all monofilaments in a textile yarn. Figure 12.11 shows the failure modes of GC1 carbon textile (Figure 12.11a) and of GC2 (Figure 12.11b) under tensile loading at room temperature. It can be seen in Figure 12.11a that, GC1 textile specimens have lost a part of its corps in the destroyed section which supported a great reaction force after the specimen failure. This apparition of the reaction force could be explained by the cause from the treatment effect of GC1 carbon textile. With the perfect pre-impregnation in an epoxy resin product, GC1 carbon textile has provided very good mechanical properties (ultimate stress, Young's modulus). So, the deformable elastic energy of GC1 carbon textile specimen was greatly accumulated inside its corps when the specimen was deformed under tensile loading. The deformable elastic energy at limited state before being broken was called rupture energy of specimen. The liberation of the rupture energy in abrupt way caused to the great reaction force in GC1 textile specimen.

Concerning the failure mode of GC2 carbon textile specimen under tensile loading at room temperature, it was also characterized by a drop in the stress on the “stress – strain” curve. However, this failure mode of textile yarn was different with two others textiles. This difference obtained was from the treatment of GC2 carbon textile. The monofilaments of GC2 textile were treated by an amorphous silica product which has

a low contribution to link between the monofilaments for joint working themselves. The samples thus badly retained their initial form. The damage appeared in a GC2 textile yarn from each small monofilaments group that had less charge capacity than the others. It means that the liberation of rupture energy was progressively realized in these monofilaments groups. That's why it can be seen the small drop in stress on the “stress – strain” curve of GC2 carbon textile. From Figure 12.11b, it could be observed the separated filament groups which has broken and separated in the GC2 carbon textile specimen.



a) Failure mode of GC1 carbon textile under tensile loading at room temperature

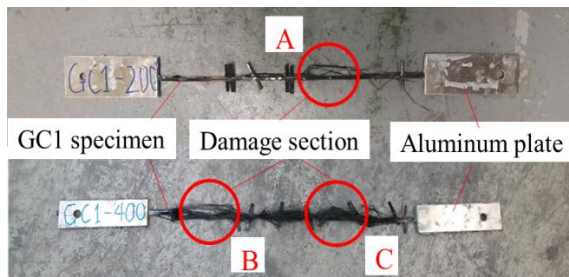


b) Failure mode of GC2 carbon textile under tensile loading at room temperature

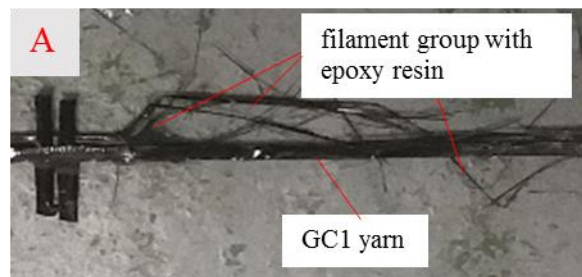
Fig 12.11: Failure modes of the test specimens of GC1 and GC2 carbon textiles under tensile loading at room temperature

At temperature ranging from 200 °C to 400 °C, the temperature action has influenced on the failure mode of three carbon textile specimens observed after thermomechanical tests. GC1 carbon textile was pre-impregnated in an epoxy resin product which has been

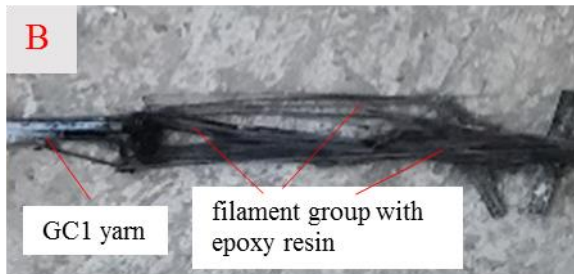
462 softened and decomposed partially (in particular at 400 °C), so it can be seen the
 463 separated filament groups with treated epoxy resin in the damage sections (see Figures
 464 12.12a,b,c,d). At 400 °C, the number of separated filament groups in damage section
 465 of GC1 specimen has increased in comparison with that at 200 °C (see Fig 12.12). It
 466 could be explained this result that the softening and melting of treated epoxy resin
 467 leaded the reduction of this product contribution for joint working of the monofilaments
 468 in textile yarn. Figures 12.12a,b,c,d below show the failure mode of GC1 carbon textile
 469 in the range of temperature from 200 °C to 400 °C.



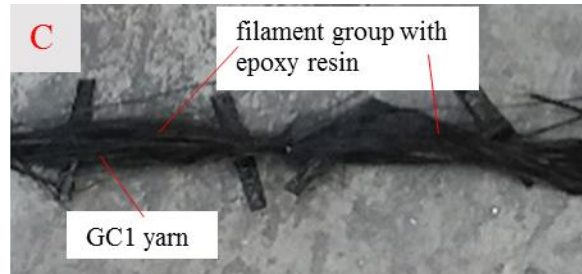
(a) GC1: Failure mode 200 °C to 400 °C;



(b) GC1 : zoom of the damage section A



(c) GC1 : zoom of the damage section B ;



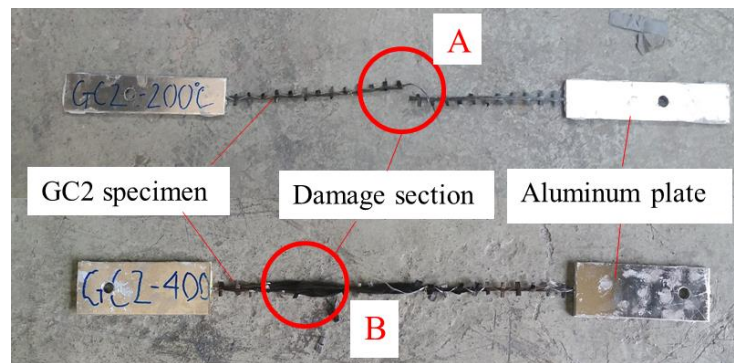
(d) GC1 : zoom of the damage section C

470 Fig 12.12: Failure mode of test specimens of GC1 carbon textile at temperature from 200 °C to 400 °C

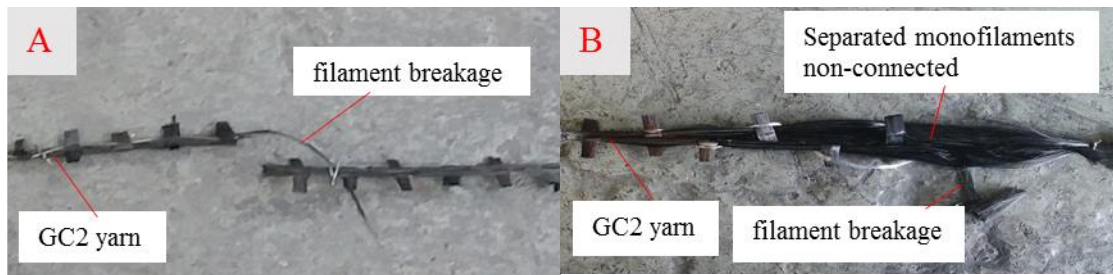
471

472 As regards to the failure mode of GC2 carbon textile in temperature from 200 °C to 400
 473 °C, it could be observed that test specimens have progressively damaged on each small
 474 group of monofilaments that had less charge capacity than the others. It was similar like
 475 that at room temperature because the coating with amorphous silica was not greatly
 476 influenced by the action of the elevated temperatures. From Figures 12.13a,b,c, it could

477 be seen that the monofilaments were separated in the damage section of GC2 textile
 478 specimens at 400 °C, and there was no-connection between themselves.



(a) GC2 : Failure mode at temperature from 200 °C to 400 °C



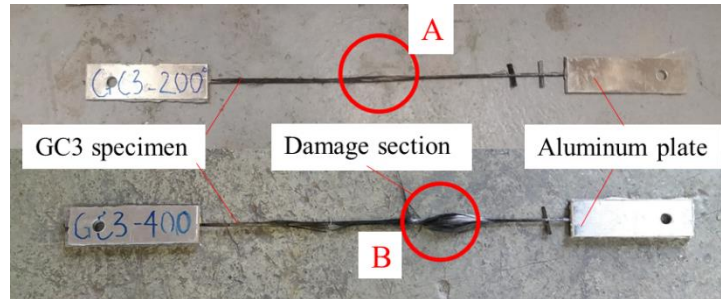
b) GC2 : zoom of the damage section A;

(c) GC2 : zoom of the damage section B

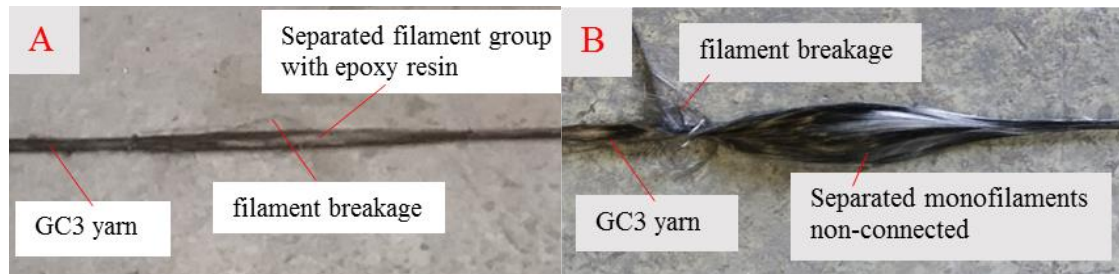
479 Fig 12.13: Failure mode of the test specimens of GC2 carbon textile at temperature from 200 °C to
 480 400°C

481 Figures 12.14a,b,c show the failure mode of GC3 textile specimens at temperatures
 482 from 200 °C to 400 °C. With a treatment by an epoxy resin product, GC3 carbon textile
 483 gave a failure mode similar like that of GC1 textile. At 200 °C, the filament breakage
 484 appeared on separated filament groups with epoxy resin in the damage section of GC3
 485 specimens. However, with low content of treatment, there was not any more epoxy resin
 486 treatment in the damage section of GC3 textile specimens at 400 °C. The
 487 monofilaments of GC3 textile yarn were separated like as the failure mode of GC2
 488 carbon textile specimen at 400 °C. The contribution of epoxy resin treatment in GC3
 489 textile yarn was similar with that of amorphous silica product in GC2 textile yarn. It

could be said that the failure mode of GC3 textile was between that of GC1 and GC2 carbon textiles.



(a) GC3 : failure mode at temperature from 200 °C to 400 °C



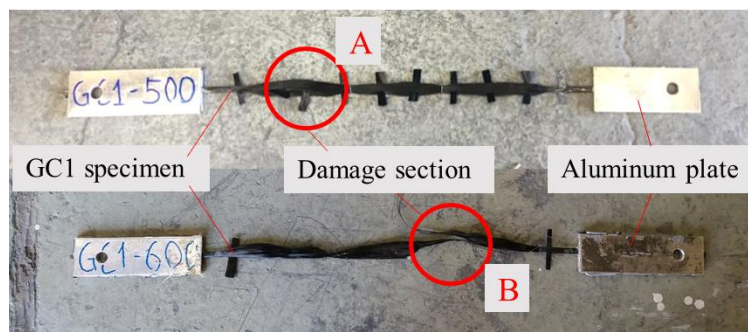
(b) Zoom of the damage section A

(c) Zoom of the damage section B

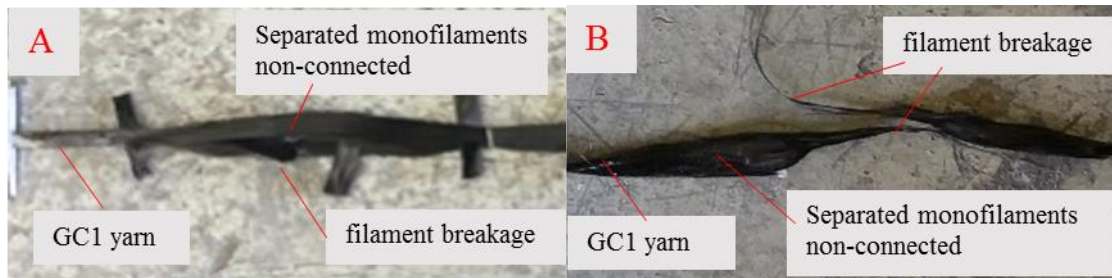
Fig 12.14: Failure mode of the test specimens of GC3 carbon textile at temperature from 200°C to 400°C

Failure modes of three carbon textiles at temperature above 400°C are shown in Figures 12.15(a,b,c) for GC1, Figures 12.16(a,b,c) for GC2 and Figures 12.17(a,b,c) for GC3. At the temperature above 400 °C, three carbon textiles gave the same failure mode which was characterized by the progressive rupture of test specimens. For the carbon textiles treated with an epoxy resin product [GC1 (Figures 12.15(a,b,c)), and GC3 [Figures 12.17(a,b,c)], the complete decomposition of pre-impregnated resin caused to the separation of the monofilaments of textile yarn. There was no connection between them for a co-working. So, the rupture energy was progressively liberated by the breakage of each monofilament in a textile yarn. The deformation of the sample increased, whereas the stress decreased progressively after reaching the maximum

504 stress value. From Figures 12.15 and 16.17, it could be observed the fibre breakage on
 505 the damage section of carbon textile specimens after the thermomechanical tests. For
 506 the carbon textile treated with an amorphous silica product [GC2, Figures 12.16(a,b,c)],
 507 it could be explained the failure mode of GC2 in the same way as that of GC1 and GC3
 508 at 400 °C. At 500 °C and 600 °C, GC2 carbon textile was partially oxidized and the test
 509 specimens are grounded by the fibre stretching. The progressive failure of each
 510 monofilament in the textile is caused mainly by this failure mode.

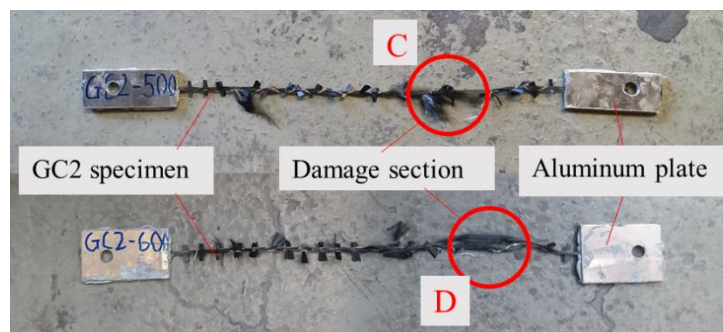


(a) GC1 : Failure mode at temperature above 400 °C

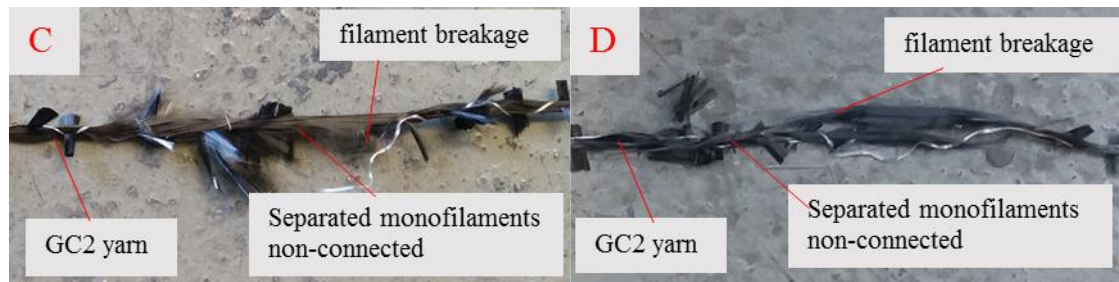


(b) GC1: Zoom of the damage section A; (c) GC1: Zoom of the damage section B

Fig 12.15: Failure mode of the test specimens of GC1 carbon textile at temperature above 400°C



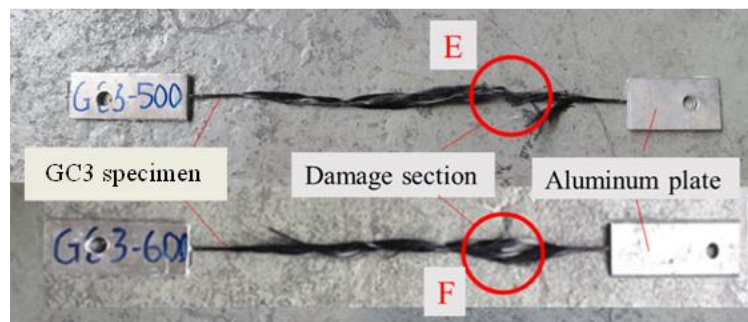
(a) GC2 : Failure mode at temperature above 400 °C



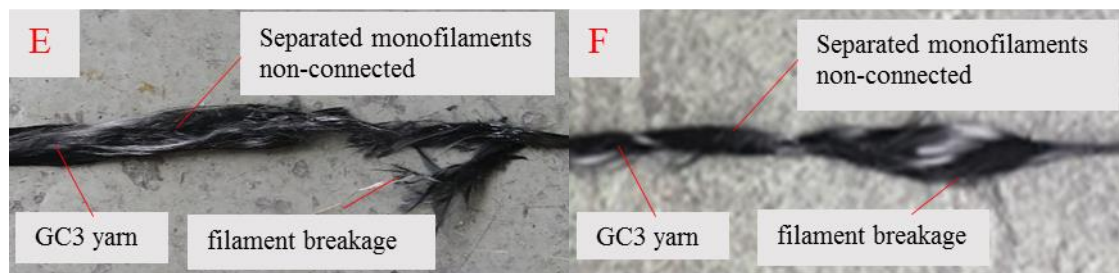
(b) GC2: Zoom of the damage section C

(c) GC2: Zoom of the damage section D

Fig 16.16: Failure mode of the test specimens of GC2 carbon textile at temperature above 400°C



(a) GC3 : Failure mode at temperature above 400°C



(b) GC3: Zoom of the damage section E

(c) GC3: Zoom of the damage section F

Fig 12.17: Failure mode of the test specimens of GC3 carbon textile at temperature above 400°C

4. Conclusions

This book chapter presents the experimental works for the characterization of the thermomechanical behaviour of carbon textiles subjected to mechanical and thermal loads. The objective of this work is to characterize the effect of textile treatment on thermomechanical behaviour and failure mode of three carbon textiles by comparing the results obtained from tests carried out on carbon textile specimens. Three carbon textiles (GC1, GC2 and GC3) have been tested under thermomechanical loading at five

temperature levels (25 °C, 200 °C, 400 °C, 500 °C, and 600 °C). All thermomechanical properties obtained such as ultimate stress, Young's modulus, and thermomechanical strain were identified and presented. As results obtained, some conclusions could be draw for this work:

1. The textile treatment by different products in nature influenced on the thermomechanical behaviour of carbon textile. Thanks to the complete pre-impregnation by the epoxy resin, the GC1 carbon textile possessed better ultimate stress and Young's modulus than the other textiles: The ratios compared between mechanical properties of GC1 textile and those of two other textiles were approximately 2 times for ultimate stress and 1.5 times for Young's modulus.
2. The treated product also influenced on the evolution of the textile mechanical properties as a function of temperature. The treatment with an amorphous silica product for GC2 textile and with very low content of epoxy resin for GC3, gave a reduction of Young's modulus with two intervals: the first one with a slight reduction (approximately 20%) in the temperature from 25 °C to 400 °C, and the second with a very significant decrease in the temperature above 400 °C, whereas the GC1 and GC3 carbon textiles (treated with an epoxy resin product) exhibited the similar reduction of ultimate stress with the increasing temperature.
3. The textile treatment also gave different failure modes of carbon textile specimens. A fragile failure mode was observed on carbon textile specimens which were treated with an epoxy resin product at moderate temperature (GC1 and GC3), whereas the carbon textile GC2 (treated with an amorphous silica product) exhibited a progressive failure of the specimens.

Recently, for an application in the electronic industries, the carbon-based conductive threads have been proposed to use as an alternative conductive thread having a flexibility and reliability, because the carbon filament has naturally very low electro-resistance. With a treatment of the polymer product, the conductive polymer-coated threads could increase its electro-resistance because of an action of the elevated temperature [36-37] and also have the failure mode as in this work. Based on the results of experimental analysis concerning the failure modes of industrial carbon textiles at elevated temperature, many solution could be suggested in order to avoid this bad results. It's possible to combine the carbon textile with a type of matrix which has good thermal capacity to give a composite material with better thermal property, or use a thermal isolation layer to protect thermally the carbon filaments and polymer treatment.

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