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MECHANICAL PROPERTIES CHARACTERISATION OF FRPS UNDER ELEVATED TEMPERATURES

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Abstract

Fiber-reinforced polymers (FRP) are rapidly gaining acceptance from the construction sector due to their large effectiveness. They are mainly used as confining reinforcement for concrete columns and as tensile reinforcement for concrete beams and slabs. FRPs are already used to a large extent at applications such as bridges and parking lots, where elevated temperatures are not the main risk. Their increasing use as structural reinforcement is hampered by the concern related with their behavior at elevated temperatures as the relevant research is deficient. Thanks to the significant advantage of FRPs' mechanical properties, further investigation into the influence of heating on their mechanical behavior may solve many doubts. The present study examines the influence of temperatures of 50, 100 and 250°C on the tensile strength of FRP laminates with carbon fibers (CFRP). In addition, the resistance of CFRP specimens to low-cycle thermal loading at the temperatures of 50, 100 and 250°C under constant tensile load was investigated. The experiments carried out in the laboratory of Experimental Strength of Materials and Structures of Aristotle University of Thessaloniki.

Keywords: fiber reinforced polymer, thermomechanical characterization, elevated temperatures, civil engineering applications.

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1 INTRODUCTION

The FRPs are composite materials consisting of continuous high-strength fibers, which are embedded into a polymer matrix (usually organic) [1]. The fibers are the reinforcing elements, whereas the polymer matrix is the connecting material which protects them and transfers the loads to and between the fibers [1]. In the construction sector, the main types of fibers used are glass, carbon (inorganic) and aramid fibers (organic polymers). The use of these materials in civil engineering applications is constantly expanding, due to their important advantages. High resistance to corrosion, high strength-to-weight ratio, high stiffness, appropriate fatigue performance, electric insulation and easy installation are some of them [2],[3]. However, FRPs, according to surveys, show sensitivity to high temperatures. Elevated temperatures cause reduction in elastic modulus and strength [2]. These possibly result in large deflections, loss of reinforcement and eventually collapse [2].

Specifically, the glass transition temperature Tg is an important parameter to be considered, as above this the mechanical characteristics of the FRPs are reduced dramatically [4]. The polymer is converted from a hard, glassy material to a soft and rubbery one [2]. This leads to loss of adhesion and fibers' removal from the matrix. The resin is no longer able to transfer the loads evenly to the fibers [4]. As a result, some of the fibers are being further loaded, probably exceed their strength and fail [4]. It is also marked that a significant increase in temperature, except in the case of fire, can be caused by direct exposure to sunlight [4]. Especially, dark surfaces are able to reach temperatures of 70°C [4].

The effects of elevated temperatures on the mechanical properties of FRPs are of concern and research into this is limited. However, thanks to the significant advantages of FRPs it is worth further investigation. The present experimental work focuses on the thermo-mechanical behavior of the CFRPs laminates under monotonic mechanical loading, low-cycle fatigue and thermal loading. The experiments carried out in the laboratory of Experimental Strength of Materials and Structures of Aristotle University of Thessaloniki and the investigation parameters were the tensile stress and the temperature.

2 MATERIALS AND METHODS

The material of the specimens which were used in the current research was FRP laminate with unidirectional carbon fiber layers embedded in organic matrix with Tg=58 °C. According to the manufacturer data sheet, layer's thickness was 0.129 mm, and the tensile strength and the elastic modulus of dry fibers were 4,000 MPa and 230,000 MPa, respectively. Twenty CFRP specimens of 250 mm length, 15 mm width and 1.8 mm thickness were prepared for the tests. (see figure 1) Their dimensions were measured using a digital caliper. Nine of them were tested at room temperature (RT=16 °C) and they were used as controls while the rest of the specimens were exposed to elevated temperatures (50, 100, 250 °C).

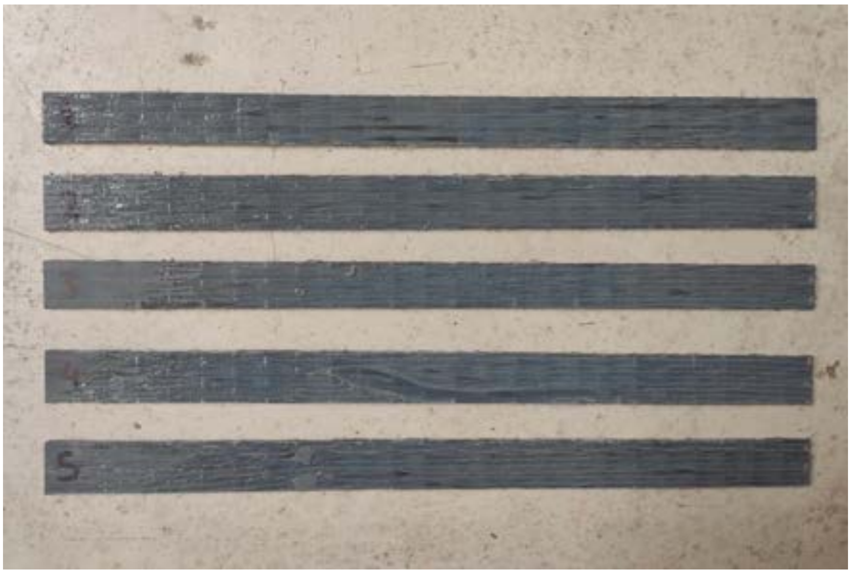


Figure 1: Investigated specimens.

The tensile tests were performed using a universal testing machine Instron of 50 kN maximum capacity. Concurrently, the Bluehill software was used for the data export. (see figure 2) A clip-on extensometer was installed in order to measure the strain values. The tensile testing was conducted using a standard head stroke rate of 2.0 mm/min until failure. The Instron machine was equipped with an electric furnace for the heating of the specimens. The maximum operating temperature of the furnace is 260 °C and the applied heating rate was 10 °C/min. The cooling up to the room temperature was held in a physical way, so the cooling rate was relatively slow. While the furnace was closed the deflection was measured by the Instron machine head stroke. The experimental setup for both room and elevated temperatures is shown in figure 3.

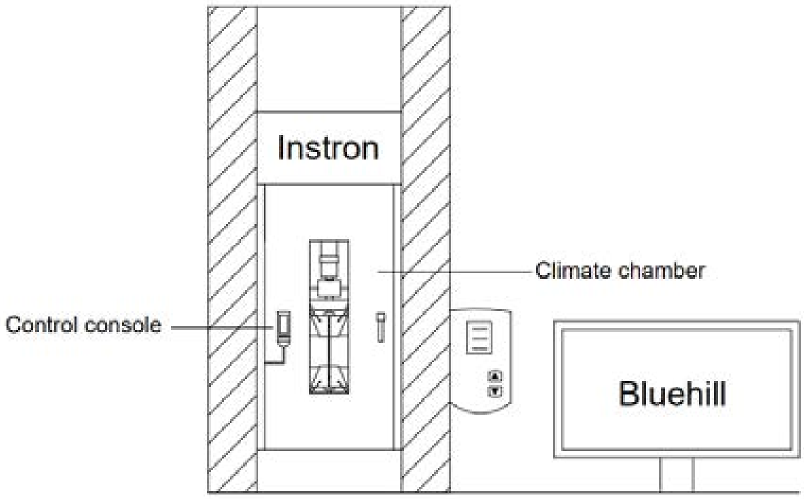


Figure 2: Experimental setup with climate chamber [5].

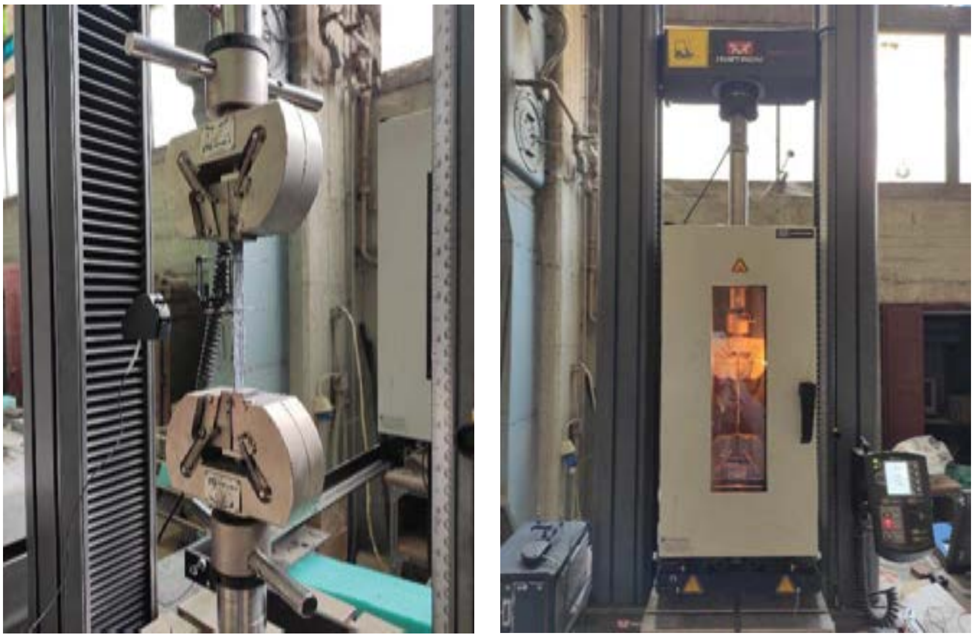


Figure 3: Experimental setup for room temperature and for elevated temperatures.

As mentioned, nine tests were occurred at room temperature (16 °C). The first five specimens (FRPspec1-5) were tested under monotonic, uniaxial tension until failure. From the average value of these specimens' strength, their maximum tensile strength was determined. Subsequently, four specimens were submitted to low-cycle fatigue tests of fifty loading-unloading cycles. The maximum load of the cycle was equal to the 50% of the average tensile strength for the two specimens (FRPspec6,14) and 75% for the other two specimens (FRPspec7,15). The rate of the tensile loading was 1000 N/min for the cyclic tests. After the fatigue loading the four specimens were tested under monotonic, uniaxial tension up to failure. The information of experiments under room temperature is shown in table 1.

Table 1: Detailed information of experiments under room temperature.

Name	Dimensions (mm)		Loading	T (°C)	Comments
	t	b			
FRPspec1	1.63	15.74	MUT*1	RT(=16)	MUT up to failure
FRPspec2	1.74	17.26	MUT	RT	MUT up to failure
FRPspec3	1.71	14.68	MUT	RT	MUT up to failure
FRPspec4	1.65	16.56	MUT	RT	MUT up to failure
FRPspec5	1.78	15.95	MUT	RT	MUT up to failure
FRPspec6	2.06	16.26	LCF*2, MUT	RT	LCF (50 cycles) with max load 50% of the tensile strength and MUT up to failure
FRPspec14	1.74	15.15	LCF, MUT	RT	LCF (50 cycles) with max load 50% of the tensile strength and MUT up to failure
FRPspec7	1.98	16.04	LCF, MUT	RT	LCF (50 cycles) with max load 75% of the tensile strength and MUT up to failure
FRPspec15	1.85	16.34	LCF, MUT	RT	LCF (50 cycles) with max load 75% of the tensile strength and MUT up to failure

*1Monotonic Uniaxial Tension, *2Low Cycle Fatigue (n=50)

The rest eleven specimens were exposed under elevated temperatures. The first six of them were submitted to thermal loading at temperatures of 50 °C (FRPspec8,11), 100 °C (FRP-spec9,12) and 250 °C (FRPspec10,13). Once the furnace reached the target temperature, each specimen remained at this temperature for 30 min in order to obtain a uniform temperature distribution. When the specimen FRPspec8 was heated at 50 °C, the uniaxial tensile test was performed at that temperature level. However, the tensile tests for the FRPspec11, the FRP-spec9,12 and the FRPspec10,13 at 50 °C, 100 °C and 250 °C, respectively, were performed after the specimens left to cool down to room temperature (16 °C). The cooling process was achieved by opening the door of the furnace. After the cooling, the specimens were tested under monotonic, uniaxial tension until failure, as described before.

In fact, CFRPs applied in concrete structures are usually under both imposed load and elevated temperatures from the environmental changes. Therefore, we decided to investigate the last five specimens under cyclic thermal loading while applying at the time uniform axial tensile loading. These specimens were subjected to monotonic, uniaxial tension constantly at 50% of their average tensile strength. A standard head stroke rate of 2.0 mm/min was used until the target load value. Then, the specimens remained under this constant axial load. After three minutes, cyclic thermal loading was imposed to the specimens. We reached the temperatures of 50 °C (FRPspec16), 100 °C (FRPspec17,18) and 250 °C (FRPspec19,20). The low-cycle thermal loading consisted of heating-cooling cycles up to failure. The maximum number of the cycles was three. Each cycle concluded the heating process with a rate of 10 °C/min, a holding time of 15 min at the target temperature and the cooling process to the room temperature (16 °C). Figure 4 presents the thermal protocol for each temperature. Specifically, the FRPspec16, which completed successfully the three thermal loading cycles, was additionally subjected to monotonic, uniaxial tension until failure at the temperature of 50 °C. The information of experiments under elevated temperature is shown in table 2.

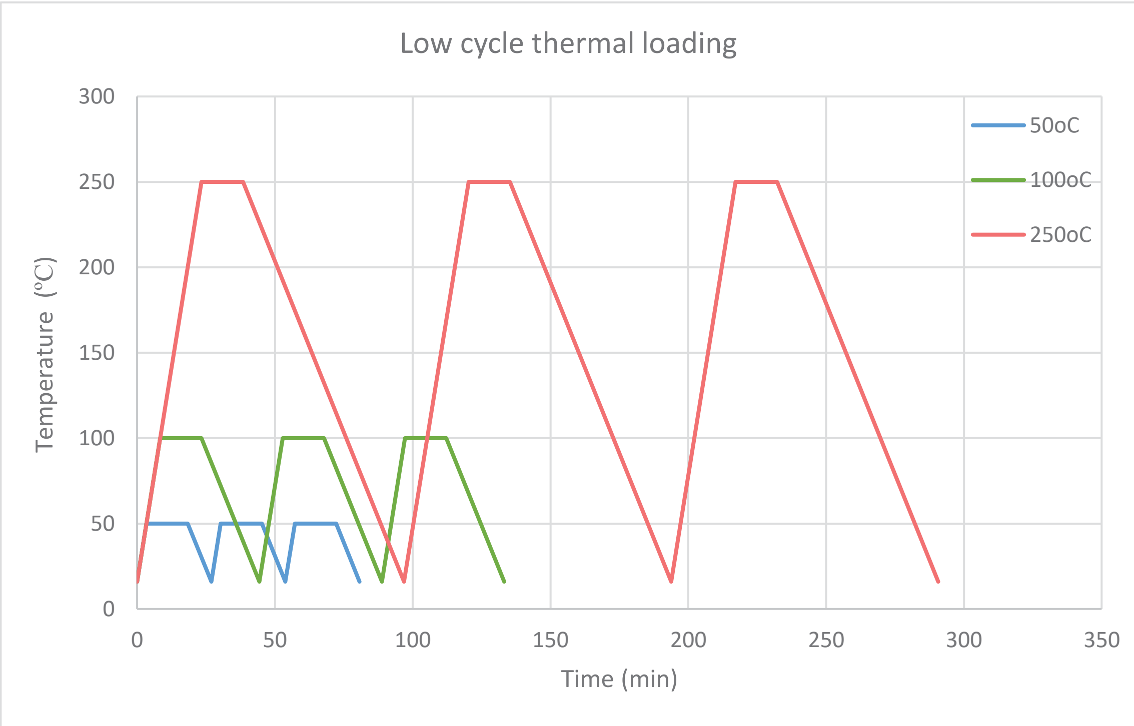


Figure 4: Time – Temperature diagram for cyclic thermal loading
(heating to 50, 100 and 250°C and cooling to RT=16°C).

Table 2: Detailed information of experiments under elevated temperatures.

Name	Dimensions (mm) t	Dimensions (mm) b	Loading	T (°C)	Comments
FRPspec8	1.90	16.25	TL*3, MUT	50	TL (1 cycle) and MUT up to failure
FRPspec11	1.99	15.96	TL, MUT	50	TL (1 cycle) and MUT up to failure
FRPspec9	1.84	16.05	TL, MUT	100	TL (1 cycle) and MUT up to failure
FRPspec12	2.04	15.76	TL, MUT	100	TL (1 cycle) and MUT up to failure
FRPspec10	1.89	15.96	TL, MUT	250	TL (1 cycle) and MUT up to failure
FRPspec13	1.78	13.98	TL, MUT	250	TL (1 cycle) and MUT up to failure
FRPspec16	1.73	14.52	MUT and LCTL*4	50	MUT with constant load 50% of the tensile strength and concurrently LCTL up to failure (max 3 cycles)
FRPspec17	1.80	14.45	MUT and LCTL	100	MUT with constant load 50% of the tensile strength and concurrently LCTL up to failure (max 3 cycles)
FRPspec18	1.71	16.68	MUT and LCTL	100	MUT with constant load 50% of the tensile strength and concurrently LCTL up to failure (max 3 cycles)
FRPspec19	1.73	13.40	MUT and LCTL	250	MUT with constant load 50% of the tensile strength and concurrently LCTL up to failure (max 3 cycles)
FRPspec20	1.87	11.05	MUT and LCTL	250	MUT with constant load 50% of the tensile strength and concurrently LCTL up to failure (max 3 cycles)

*3Thermal Loading, *4Low Cycle Thermal Loading (n=3)

3 RESULTS

Table 4 presents the results of all the CFRP specimens. Concerning to the control specimens, the average tensile strength of dry fibers of the specimens FRPspec1-5, which were monotonically loaded at room temperature up to failure, was 4,410.82 MPa, their average ultimate strain was 17.47‰ and their average elastic modulus of dry fibers was 252.52 GPa. Their stress-strain curves are shown in figure 5.

Table 4: Summarized results

Name	Loading	T (°C)	Max Tensile Stress (MPa)	Max Tensile Stress of dry fibers (MPa)	Max Strain (‰)	Elastic Modulus of dry fibers (GPa)	Comments / Mode of failure
FRPspec1	MUT	RT(=16)	719.59	4,546.28	17.86	254.61	Fracture of fibers
FRPspec2	MUT	RT	664.65	4,482.52	16.75	267.61	Fracture of fibers
FRPspec3	MUT	RT	657.99	4,361.10	18.53	235.35	Fracture of fibers
FRPspec4	MUT	RT	711.28	4,548.91	18.39	247.36	Fracture of fibers
FRPspec5	MUT	RT	596.49	4,115.30	15.81	260.30	Fracture of fibers
FRPspec6	LCF, MUT	RT	565.99	4,519.17	20.45	220.98	Fracture of fibers
FRPspec14	LCF, MUT	RT	646.27	4,358.59	21.69	200.98	Fracture of fibers

FRPspec7	LCF, MUT	RT	531.52	4,079.09	16.12	253.08	Fracture of fibers
FRPspec15	LCF, MUT	RT	612.95	4,395.18	18.84	233.25	Fracture of fibers
FRPspec8	TL, MUT	50	490.90	3,615.14	13.67	264.52	Fracture of fibers
FRPspec11	TL, MUT	50	569.99	4,396.47	17.68	248.67	Fracture of fibers
FRPspec9	TL, MUT	100	393.61	2,807.13	10.14	276.95	Fracture of fibers
FRPspec12	TL, MUT	100	518.15	4,097.00	27.66	148.11	Fracture of fibers
FRPspec10	TL, MUT	250	577.98	4,234.06	15.51	272.99	Fracture of fibers
FRPspec13	TL, MUT	250	669.88	4,621.66	19.60	235.80	Fracture of fibers
FRPspec16	MUT and LCTL	50	*356.98* *487.61*	*2,393.71* *3,269.66*	15.21 19.32	 *169.27*	It completed successfully the three thermal loading cycles. *The values of the first line refer to the LCTL under constant tension and the values of the second line refer to the MUT up to failure.*
FRPspec17	MUT and LCTL	100	*348.07*	*2,428.37*	12.95	*187.46*	Failure at the heating process of the first cycle at 64°C. *The values refer to the LCTL under constant tension.*
FRPspec18	MUT and LCTL	100	*317.71*	*2,105.78*	24.14	*87.23*	Failure at the cooling process of the first cycle at 31°C. *The values refer to the LCTL under constant tension.*
FRPspec19	MUT and LCTL	250	*388.48*	*2,604.95*	15.55	*167.53*	Failure at the heating process of the first cycle at 61°C. *The values refer to the LCTL under constant tension.*
FRPspec20	MUT and LCTL	250	*327.22*	*2,371.75*	23.63	*100.36*	Failure at the heating process of the first cycle at 151°C. *The values refer to the LCTL under constant tension.*

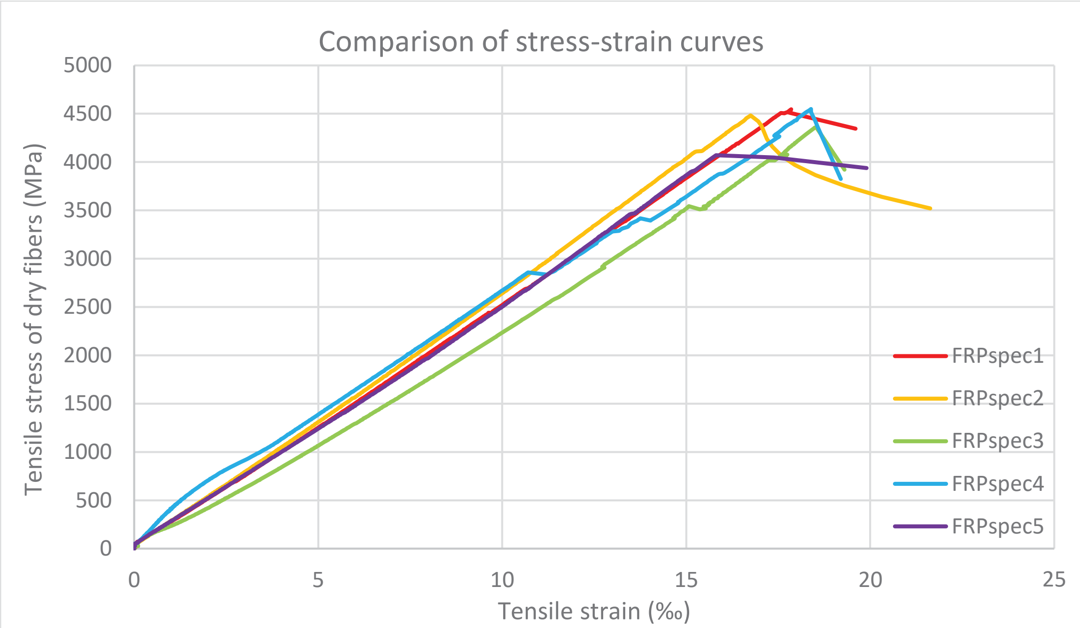
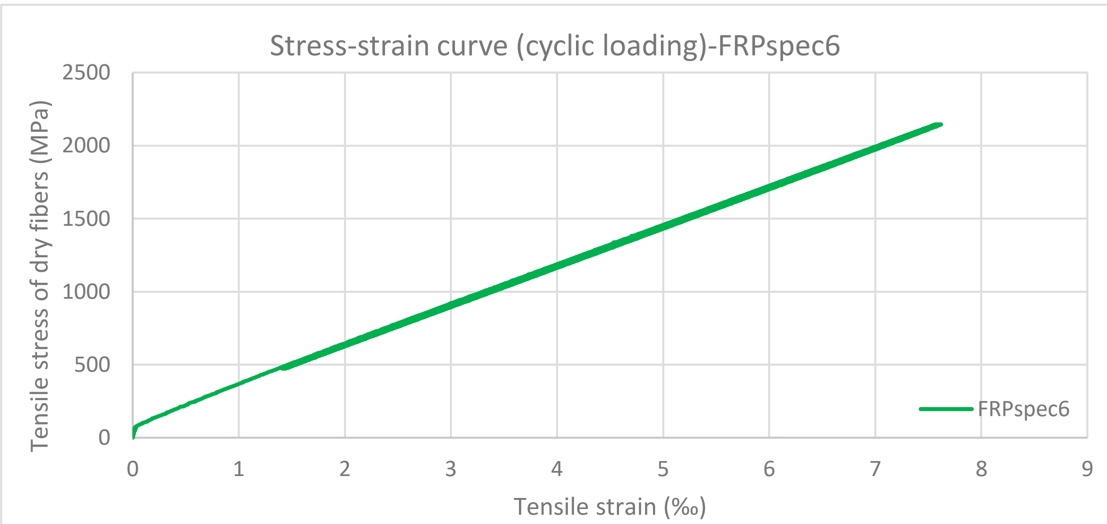


Figure 5: Stress-strain curves for monotonic uniaxial tension at room temperature.

The specimens FRPspec6,14 and FRPspec7,15 were submitted to fatigue tests of fifty loading-unloading cycles with maximum load of 50% and 75% of the average tensile strength, respectively. (see figure 6) Resulted from the monotonic, uniaxial tension that followed, the average tensile strength of dry fibers was 4,438.88 MPa and 4,237.14 MPa for the FRPspec6,14 and the FRPspec7,15, respectively. Consequently, the low-cycle fatigue did not affect the specimens FRPspec6,14, but it reduced the CFRPs tensile strength of dry fibers by 3.94% for FRP-spec7,15. Besides, the average ultimate strain did not appear significant change as its value was 21.07‰ and 17.48‰ for the FRPspec6,14 and the FRPspec7,15, respectively. It should also be mentioned that low-cycle fatigue does not affect the stiffness of the CFRPs as their elastic modulus of dry fibers remain at the same level. The stress-strain curves of monotonic tensile loading of the specimens are shown in figure 7.



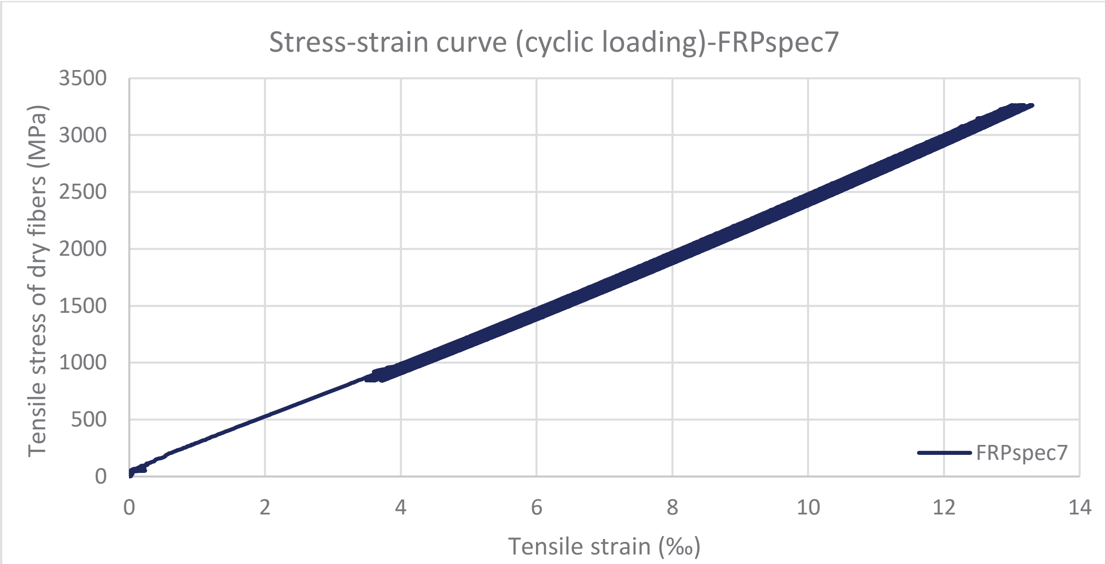


Figure 6: Stress-strain curves for low-cycle fatigue
with max load 50% (FRPspec6) and 75% (FRPspec7) of the tensile strength.

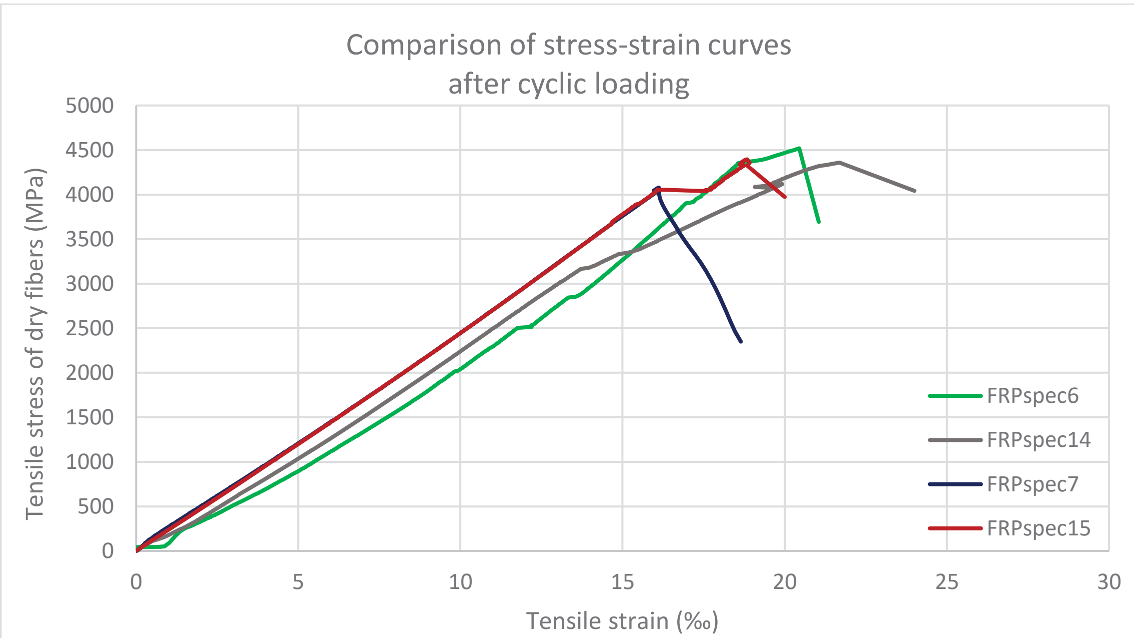


Figure 7: Stress-strain curves of monotonic, uniaxial tension at room temperature after low-cycle fatigue.

The specimens FRPspec8-13,16-20 were exposed to different temperatures during the experiments as it mentioned before. Figure 8 presents the stress-strain curves of monotonic, uniaxial tensile tests which were conducted after the specimens' heating and cooling (FRPspec8-13). FRPspec8 is an exception as the tensile test was possible to be held at the temperature of 50 °C without slip of the specimen. The specimen's tensile strength of dry fibers was 3,615.14 MPa and its ultimate strain was 13.67‰. Observing the samples after heating, those exposed to 100 and 250 °C softened a lot and the resin turned easily into powder with the application of pressure by the machine. In addition, the FRPspec10,13 acquired a dark black colour. However, it was observed that the samples regained their hardness after cooling and the resin was no longer frail. A worth noting conclusion is that the tensile strength of dry fibers of the specimens after exposure at the temperatures of 50, 100 and 250 °C for 30 min did not appear decrease.

The fact that the samples were left to cool significantly contributed to this result. The ultimate strain and the elastic modulus of dry fibers of these specimens did not appear any important change, too.

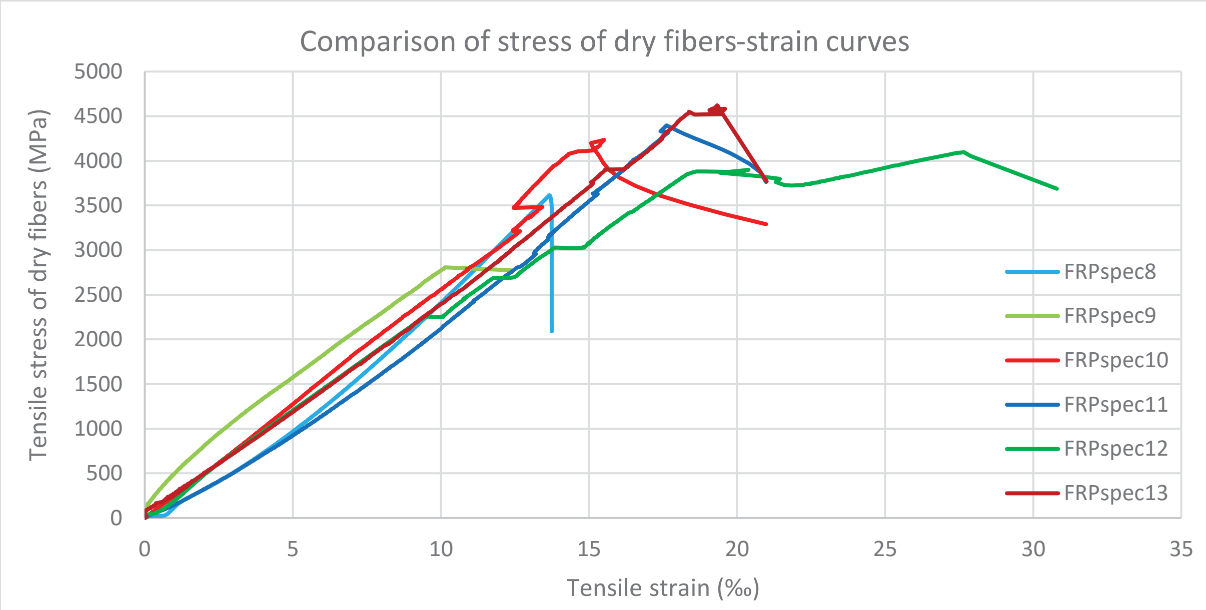


Figure 8: Stress-strain curves of monotonic, uniaxial tensile tests after exposure to the temperatures of 50 °C (FRPspec8,11), 100 °C (FRPspec9b,12) and 250 °C (FRPspec10,13) and then cooling.

The specimens FRPspec16-20 were under both constant tensile load and thermal loading of maximum three heating-cooling cycles. The stress-strain curves of these tests are shown in figure 9. The only sample which managed to complete three heating-cooling cycles without failure was FRPspec16. The maximum temperature of each cycle at this test was 50 °C. After the thermal cyclic loading, FRPspec16 was tested under monotonic tension. The specimen's tensile strength of dry fibers was 3,269.66 MPa, its ultimate strain was 19.32 ‰ and its elastic modulus of dry fibers was 169.27 GPa. According to this, the tensile strength and the elastic modulus of dry fibers are decreased after the heating-cooling cycles.

At higher temperatures, heating combined with the continuous loading had an important impact on the CFRPs' strength as the four samples failed during the first cycle. FRPspec17 failed at the heating process at 64 °C, FRPspec18 failed at the cooling process at 31 °C, FRPspec19 failed at the heating process at 61 °C and FRPspec20 failed at the heating process at 151 °C. The first two of these samples were supposed to be exposed to maximum temperature of 100 °C and the last two to maximum temperature of 250 °C.

It is necessary to mention that the heating rate was 10 °C/min. Because of this slow rate, the specimens remained at high temperature for a long time. If the heating rate was faster, may the FRPs resisted for more thermal loading cycles. The deterioration of the CFRP, due to the long time remaining at high temperature, was also obvious from the mode of failure of the FRPspec20 and its fibers' dark colour. Some of the specimens which were exposed to elevated temperatures are shown after their failure in figure 10.

From the specimens which were supposed to be exposed to maximum temperature of 100 °C and 250 °C, the FRPspec18 and FRPspec20 remained at high temperatures for a longer time than the FRPspec17 and the FRPspec19, which failed earlier. It is also evident from the figure 9 that staying at high temperatures under constant load for longer time causes greater deflections and significant reduction in the modulus of elasticity. The ultimate strain and the elastic modulus of dry fibers of the FRPspec18 were 24.14 ‰ and 87.23 GPa, respectively, and of the FRPspec20 were 23.63 ‰ o and 100.36 GPa, respectively.

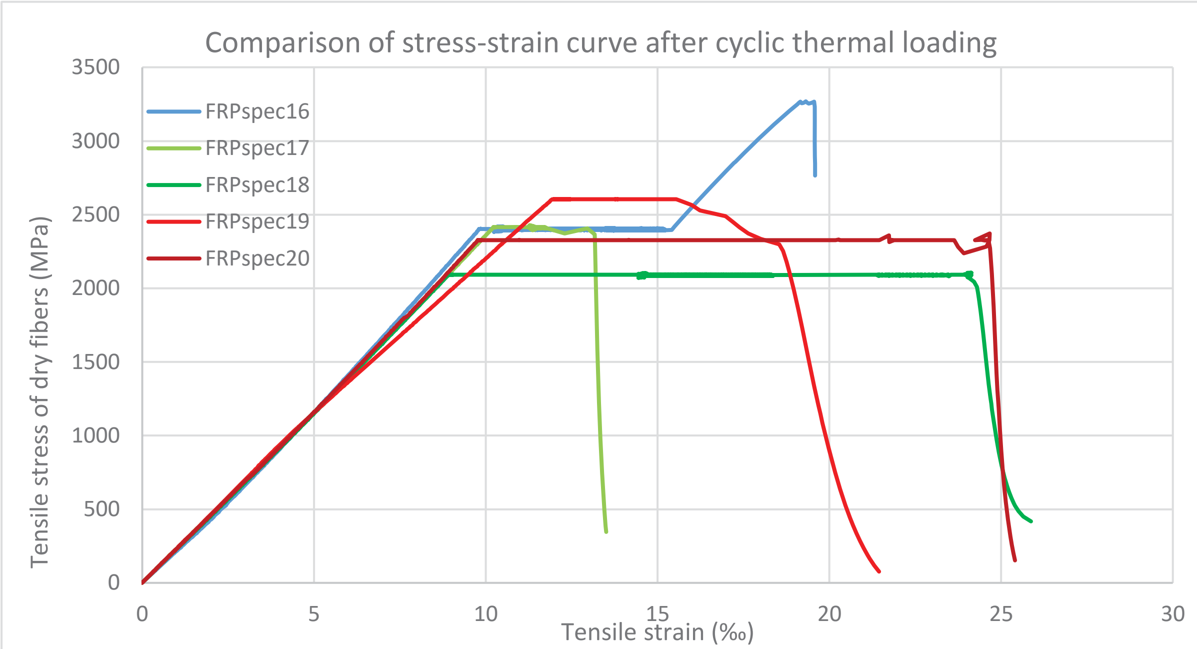


Figure 9: Stress-strain curves of low-cycle thermal loading under constant tensile load. The maximum temperatures of heating-cooling cycles were 50 °C (FRPspec16), 100 °C (FRPspec17,18) and 250 °C (FRPspec19,20).

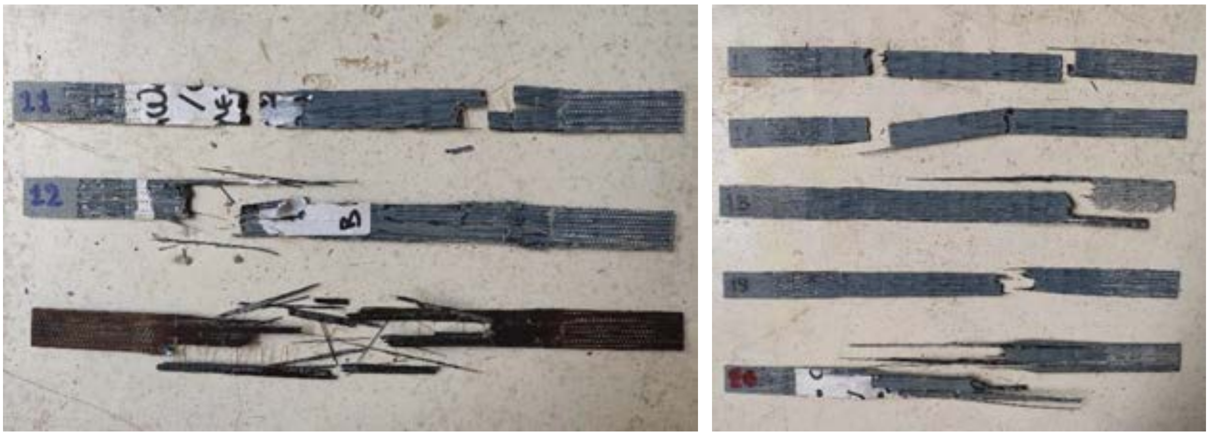


Figure 10: Specimens, exposed to elevated temperatures, after their failure.
FRPspec11,12,13 were exposed to 50,100 and 250 °C, respectively (TL, MUT).
FRPspec16, FRPspec17,18 and FRPspec19,20 were exposed to 50,100 and 250 °C, respectively (MUT and LCTL).

4 CONCLUSION

- At room temperature CFRP laminates appear high tensile strength and elastic modulus.
- Low-cycle fatigue at room temperature reduces in a small percentage the CFRP laminates' tensile strength. This reduction is obvious when the maximum load of the cycle is high enough.
- Low-cycle fatigue at room temperature does not affect the stiffness of the CFRPs, as their elastic modulus remain at the same level.

- When CFRP laminates are exposed to elevated temperatures (100 °C, 250 °C) the resin softens and turns easily into powder if pressure is applied. In addition, the FRPs acquire a dark black colour at 250 °C.
- Because of the resin's deterioration under elevated temperatures, the CFRP specimens slip from the machine's grips during the tensile testing. Therefore, better gripping is needed.
- CFRPs cooled after exposure to elevated temperatures, regain their hardness and the resin is no longer frail. Their tensile strength does not show decrease.
- The cyclic thermal loading under constant tensile load causes degradation of CFRP laminates, as their tensile strength is reduced after the heating-cooling cycles.
- The cyclic thermal loading under constant tensile load reduces the elastic modulus of CFRP laminates. The higher temperatures the CFRPs are exposed to, the greater reduction of the elastic modulus is caused.
- The longer time the CFRP laminates remain at high temperatures under constant tensile load, the greater deflections and reduction in their elastic modulus are caused.

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