EXPERIMENTAL STUDY ON TRANSIENT THERMAL PERFORMANCE OF P-CFRP UNDER TENSILE LOADING AND CLOSE-TO-FIRE CONDITION

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***Abstract**: Pultruded carbon fibre reinforced polymer (P-CFRP) is popular used in flexural-strengthening civil engineering structures such as beams, slabs, and walls. When a fire happens, these structures and reinforced materials are simultaneously exposed to both high temperatures (potentially up to 1200°C) and mechanical loadings at the same time. This combined condition is complicated and difficult to be replicated in experimental investigation. Therefore, the studies of CFRP and structure reinforced with CFRP in fire are rare due to expensive cost of experiments and insufficient theoretical calculations. For these reasons, this study aims to investigate the performance of P-CFRP in transient thermal and mechanical conditions that close to fire, regarding the simultaneousness of these effects. In the test condition, the mechanical load is applied on P-CFRP material and then maintained; the temperature surrounding P-CFRP material is then increased with the heating rate up to 30°C/minute until rupture. The P-CFRP specimen has been tested at several mechanical levels corresponding to from 10% to 68% of its ultimate strength at 20°C. The result shows that when the mechanical load increases from 10% to 50% of its ultimate strength at 20°C, the temperature, at which P-CFRP failure, gradually decreases. When the mechanical load increases to 68% of its ultimate strength at 20°C, the failure temperature of P-CFRP significantly reduces. The experimental result also indicates that, as the heating rate increases from 2°C/minute to 26°C/minute, the failure temperature increases up to 14.6%. The obtained result well confirms the combined influence between thermal and mechanical loadings on the performance of P-CFRP at thermo-mechanical conditions, disregarding the sequence of loads. The failure mode of P-CFRP at different studied cases will also be discussed.*

***Keywords**: pultruded carbon fibre reinforced polymer (P-CFRP), elevated temperature, thermo-mechanical behaviour, close-to-fire condition.*

***Classification number:** 2.4*

1. Introduction

The change in usage, the structural degradation, or even insufficient design leads to the demand for reinforcing/retrofitting of concrete and steel structures. Using CFRP is a common and traditional reinforcement solution because of its advantages in mechanical properties, corrosion resistance, durability as well as workability. The material can be directly bonded to concrete surface or via dipping CFRP in to trenches on concrete surface with adhesive paste depending on structure and particular condition. Since its initial applications, fire concern is always a critical weakness of its application because it simultaneously involves both elevated temperature and mechanical load. A recent literature review done by Firmo et al. [1] has summarized several experimental and analytical fire-concerned studies on CFRP. Most of these studies focused on the residual properties of CFRP after exposing to elevated temperature while few concentrated on the CFRP properties under elevated temperature condition. Furthermore, majority of these studies considered temperature increase then mechanical load order instead of mechanical load then temperature increase, which is closer fire-condition. In general, the mechanical properties of CFRP (ultimate strength and Young's modulus) are reported to reduce as the temperature level increases, for both under and after exposing to elevated temperature condition. Particularly, Y.C. Wang et al. performed a series of tensile tests on CFRP rod at temperature ranging from

20°C to 600°C following thermo-mechanical procedure [2]. K. Wang et al. measured the tensile strength of the pultruded CFRP strip following thermo-mechanical procedure at temperature ranging from 22°C to 706°C [3]. Yu and Kodur studied the influence of temperature between 20°C to 600°C on the degradation of tensile properties of pultruded CFRP products (strips and rods) following thermo-mechanical procedure [4]. Cao et al. tested the thermo-mechanical tensile strength of CFRP sheets with two different methods of loading control (by load increment and displacement increment) at the temperature between 16°C and 200°C [5]. Recently, Nguyen et al. has compared residual and thermo-mechanical properties of a pre-fabricated CFRP (or pultruded CFRP) under temperature condition between 20°C and 700°C [6]. Generally, it is reported that the ultimate strength of CFRP gradually reduced as the temperature increased from room temperature to about 700°C whereas its Young's modulus was little affected until 400°C and significantly reduced beyond this temperature. The thermo-mechanical condition, in which mechanical load and then elevated temperature are in turn applied, is never studied before. Moreover, in standard fire-condition, the temperature-increase rate is up to 110°C/minute while in most of the previous studied cases, material was studied with much lower rate (from 3°C/minute [5] to 5-10°C/minute [4] and 50°C/minute [3]). Therefore, this study aims to investigate the ability to resist the elevated temperature of mechanically loaded P-CFRP material, regarding the missing case-study in the literature which is closer to the real fire condition regarding simultaneousness of loads and their acting order. The influence of heating rate on the thermal performance of P-CFRP is also studied. In the followings, this paper presents an experimental method in which the experimental devices, the specimens, and the test procedure are detailed. It then describes and discusses the results of tests carried out on the studied material. The presentation of the main conclusion ends this paper.

2. Experimental method

This research focuses on the thermal resistance of CFRP material at different mechanical status. The thermo-mechanical system [6] was used to experimentally study the thermal resistance of CFRP subjected to different mechanical conditions. This thermo-mechanical system can apply the mechanical load up to 20kN and temperature potentially up to 1200°C with maximum heating rate up to 30°C/minute.

2.1. Material and specimen preparation

The CFRP used in this study is an prefabricated product (or pultruded CFRP, P-CFRP) provided by the laboratory' partner: Sika® CarboDur® S512 which contains 68% of carbon fibre and with tensile strength at about 2800 MPa and Young's modulus is 165GPa (according to supplier's datasheet). The designed specimen, described in Figure 1, is prepared from the standard laminate CFRP product (50 mm x 1.2 mm of cross-section and 50 m of length). Based on the standard on tensile test, CFRP specimen is bonded with two aluminium plates at each end so that it can improve the connection between CFRP specimens and loading heads testing system [6]. The aluminium plates are bonded to CFRP using two-component epoxy named Eponal 380. After 7 days of ambient temperature curing condition, two holes are drilled and CFRP plate is trimmed according to the designed dimensions (Figure 2).

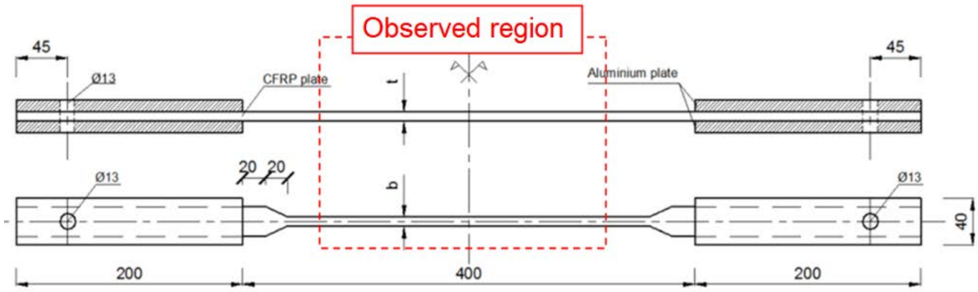


Figure 1. *Design of CFRP specimen.*
(t = 1.2 mm: thickness of CFRP plate; b~6-8mm: width of CFRP plate)

a) b)

Figure 2. Preparation of samples
a) Bonding of aluminium plates to CFRP laminate b) Completed CFRP specimen

2.2. Testing program

The CFRP specimen is tested following a modified thermo-mechanical procedure from the previous publication [6]. This procedure, called constant-load thermo-mechanical test, is to identify the failure temperature corresponding to mechanical load that is imposed on the specimen. Figure 3 presents the evolution of temperature and mechanical loading during this test procedure. Particularly, the specimen is firstly applied with a pre-determined load called applied load (Fa). Then, in the next phase, during the Fw is maintained, the temperature surrounding the specimen increases with the heating rate at 30°C/minute from ambient temperature until rupture. With this applied heating rate, the temperature evolution in the furnace can reach 900°C after 30 minutes, which is close to the fire-temperature condition (Figure 4). The temperature, at which specimen is broken, is identified as failure (or rupture) temperature (Tr) corresponding to Fw; and the duration from the beginning of temperature rise until the failure of specimen is identified as exposure duration corresponding to Fw. The value of Fw is identified based on the ultimate load of CFRP material obtained at ambient temperature condition:

$$F_a = f_a \cdot F_{u(20°C)} \qquad (1)$$

In which: fa is stress ratio and Fu (20°C) is the ultimate force obtained at 20°C

Table 1 summarizes the experimental tests conducted in this study with the variation in stress ratio and heating rate that varies from 2°C/minute to 30°C/minute for stress ratio of 0.25 and is 30°C/minute for other stress ratios.

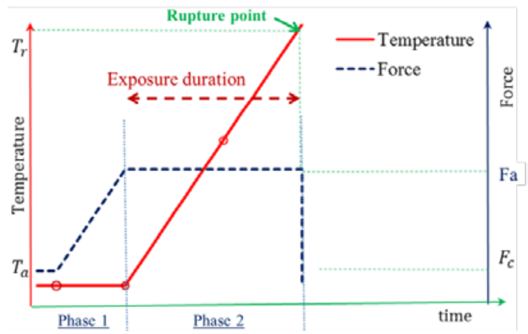


Figure 3. *Thermo-mechanical testing regime; Ta: ambient temperature; Tr: rupture temperature; Fc: control force; Fa: applied force.*

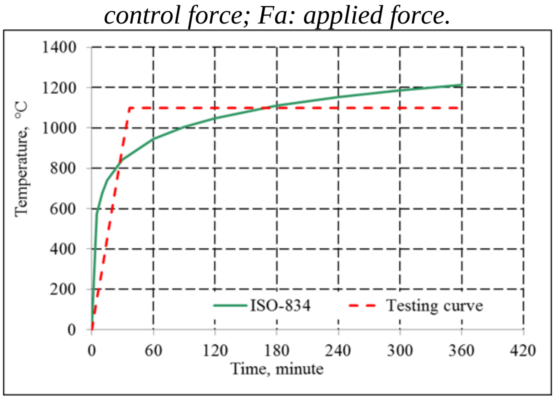


Figure 4. *Standard fire curve and programmed temperature-time curves.*

Table 1. *Summary of the conducted tests.*

Sample (*)	Stress ratio, f_a	Heating rate	Number of tests
		°C /minute	
P.TM.10.1÷2	0.1	30	2
P.TM.25.1÷6	0.25	2-30	6
P.TM.50.1÷2	0.5	30	2
P.TM.68.1	0.68	30	1

(*)Meaning of the name of sample: P: Pultruded CFRP; TM : Thermo-mechanical testing regime (as shown in Figure 3); 10, 25, 50, 68 : Percentage of applied forces versus the P-CFRP ultimate force at 20 ° C (that is equal to 100.fa); 1÷n : number of tests carried out on the same condition.

3. Experimental result

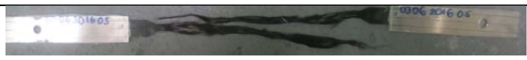
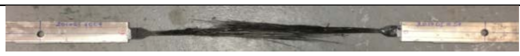
The average ultimate strength obtained from the P-CFRP at 20°C is 2389.42 MPa [6], from which the applied load at each stress ratio is identified (Table 1). Table 2 presents the experimental results of P-CFRP material with failure temperature, exposure duration and mean heating rate in each test. According to these results, the failure temperatures at the stress ratios of 0.1 and 0.25 little scatter but are close at the stress ratio of 0.5. As can be seen from Table 2, the mean heating rate varies a wide range despite of the fixation of programmed heating rate at 30°C/minute. This leads to the scatter of exposure duration in same stress-ratio case. According to Table 2, the failure temperature of CFRP reduces significantly to 41°C at the stress ratio 0.68. Therefore, the observed stress ratio is not further increased.According to Table 3, with the stress ratio varies from 0.1 to 0.5, the failures of P-CFRP resulted from the break of carbon fibres at elevated temperature (ranges from 384°C to 712°C, which is beyond the decomposition temperature of common thermosetting polymer). It is because at the end of the experiment, there is only carbon fibres left within the specimen (mode I). At a stress ratio of 0.68, the polymer matrix does not melt and still contribute to the material resistance until the fragile rupture of both fibre and matrix at the end of the test (mode II). These failure modes consist with the previous study carried out by Nguyen et al. [6] under constant elevated temperature condition regarding the range of failure temperature.

Table 2. *Performance of P-CFRP at different stress ratios.*

No	Sample	Stress ratio, f_a	Failure temperature	Exposure duration	Mean heating rate
			°C	min	°C/min
1	P.TM.10.1	0.10	712	39.7	16.6
2	P.TM.10.2	0.10	686	47.6	13.3
3	P.TM.25.1	0.25	669	27.3	26.4
4	P.TM.25.2	0.25	609	28.3	19.9
5	P.TM.25.3	0.25	601	47.1	12.3
6	P.TM.25.4	0.25	649	34.7	16.7
7	P.TM.25.5	0.25	664	25.2	25.6
8	P.TM.25.6	0.25	584	258.8	2.1
9	P.TM.50.1	0.50	489	50.3	10.5
10	P.TM.50.2	0.50	384	14.3	23.0
11	P.TM.68.1	0.68	41	1.0	15.0

Table 3. *Typical failures of the tested samples.*

Stress ratio, f_a	Samples	Failure images	Failure modes
0.10	P.TM.10.01		I
	P.TM.10.02		I

Stress ratio, f_a	Samples	Failure images	Failure modes
0.25	P.TM.25.01		I
	P.TM.25.02		I
0.50	P.TM.50.01		I
	P.TM.50.02		I
0.68	P.TM.68.02		II

4. Discussion

This section discusses the results obtained for the effect of heating rate on thermal resistance of P-CFRP subjected to the stress ratio of 0.25 and explains the evolution of thermal resistance of P-CFRP according to the applied load. Furthermore, the dependent correlation between temperature and mechanical statuses on performance of P-CFRP is discussed.

4.1. Effect of heating rate on thermal resistance of P-CFRP subjected to the stress ratio of 0.25

Table 4 shows the P-CFRP failure temperatures obtained at different heating rates when the material is subjected to the same stress ratio of 0.25. Figure 5 presents the variation of failure temperatures at different mean heating rates (for the same stress ratio of 0.25). It is indicated that under the same stress ratio of 0.25, the P-CFRP failure temperature gradually increases from 584°C to 669°C as the heating rate increases from 2.1°C/minute to 26.4°C/minute. The maximum variation of failure temperature is 7.15% at the heating rate of 2.1°C/minute compared to average failure temperature ($\overline{T_r}$). With the heating rate between 10°C/min and 25°C/min, the variation is small and less than 5% (compared with $\overline{T_r}$). It is because, without mechanical load, the failure of PAN-based carbon fibre (used to fabricate the studied P-CFRP) only depends on the oxidation process of carbon filament [7]. According to Yin et al., the endothermic reaction of PAN-based carbon fibre is little affected by the temperature evolution that is under 800°C [8]. In this study, the direct contact between carbon fibres, oxygen and temperature is limited and the temperature evolution on carbon fibre surface depends on the heat transfer within structure of composite material. However, under the mechanical action on the material, the failure temperature range (from 584°C to 669°C) is lower than the oxidation temperature range of carbon fibre (Table 4).

Table 4. *Failure temperatures at different heating rates (f_a= 0.25); $\overline{T_r}$: average failure temperature; $\overline{T_r}^{\,i}$: failure temperature for the concerned test (i).*

Heating rate, °C/minute		Failure temperature (Tr,°C)	$\left\lvert T_r^i - \overline{T_r} \right\rvert$, °C	Difference (%)
Programed heating rate	Mean heating rate			
2	2.1	584	45	7.15
10	12.3	601	28	4.45
15	16.7	649	20	3.18
20	19.9	609	20	3.18
25	25.6	664	35	5.56
30	26.4	669	40	6.36
Average failure temperature $\overline{T_r}$		629		

4.2. Evolution of thermal resistance of P-CFRP according to the applied load

Table 5 presents failure temperature and exposure duration at different stress ratios obtained in Table 2 regarding cases with mean heating rate that varies from about 15°C/minute to 20°C/minute. Figures 6 and Figure 7 show the evolution of the failure temperature and exposure duration of P-CFRP at different stress ratios.

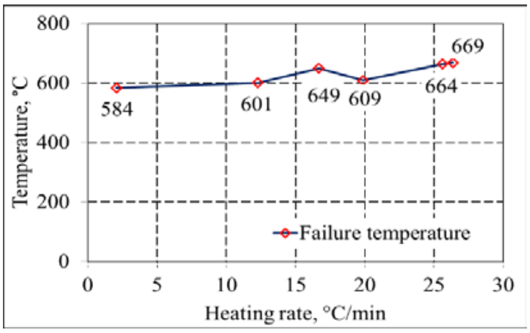


Figure 5. *Variation of failure temperature of P-CFRP at different heating rates (for the same stress ratio of 0.25).*

Table 5. *Average failure temperature and exposure duration of P-CFRP.*

Stress ratio, f_a	Average failure temperature	Average exposure duration
	°C	min
0.1	699	44.0
0.25	649	35.0
0.5	436.2	32.3
0.68	41	1.0

From table 1, figures 6 and figure 7, when the stress ratio increases from 0.1 to 0.25, the failure temperature gradually decreases from 600°C to 649°C while the exposure duration decreases from 44 minutes to 35 minutes. At the stress ratio of 0.5, the failure temperature reduces to 436.2°C while the exposure duration slightly reduces to 32.3 minutes. At the stress ratio of 0.68, the thermal resistance of P-CFRP significantly reduces to 41°C (with failure temperature) and 1 minute (with exposure duration) respectively. This evolution is similar to the experimental results conducted on a hand lay-up CFRP by Nguyen et al. [9].

4.3. Dependent correlation between temperature and mechanical statuses on performance of P-CFRP

Figure 8 displays the correlation between the evolutions of "failure temperature at different mechanical statuses" (Curve 2) obtained in this study and "ultimate strength at different constant temperature levels" (Curve 1) for the P-CFRP.

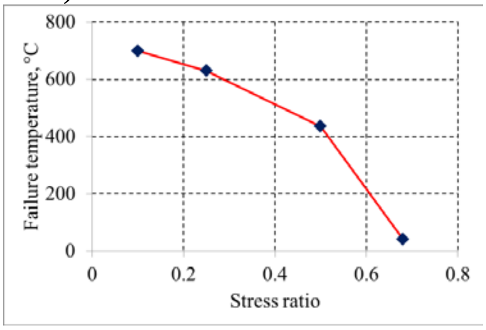


Figure 6. *Evolution of the failure temperature of P-CFRP as a function of the stress ratio.*

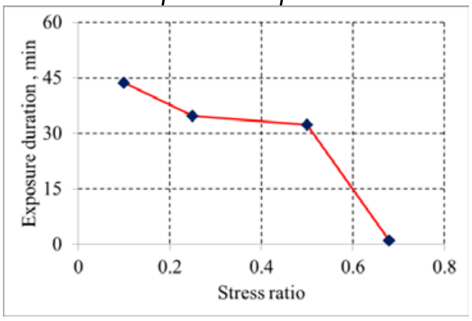


Figure 7. *Evolution of the exposure duration of P-CFRP as a function of the stress ratio.*

The difference between two results is that the order of temperature and mechanical loads. In this study, the mechanical load is applied and maintained first and then the temperature increases while in the previous study by Nguyen et al. [6], the temperature is applied and maintained during one hour before the quasi-static mechanical load is applied. These two results show that the mechanical status and applied temperature have mutual quasi-static mechanical load is applied. These two results show that the mechanical status and applied temperature have mutual influence on the performance of P-CFRP. When being exposed to increasing temperature, the mechanical resistance of P-CFRP reduces and vice versa, when being applied with increasing mechanical status, the thermal resistance of this material reduces.

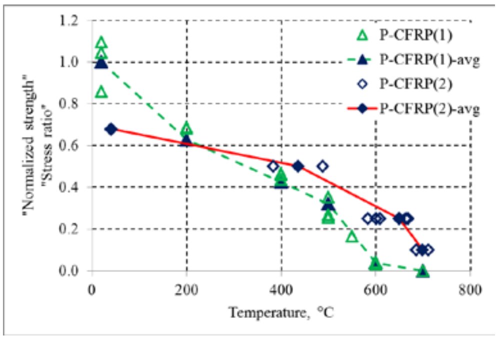


Figure 8. *Correlation between "failure temperature at different constant mechanical statuses" (curve 2) and "ultimate strength at different constant temperature levels" (curve 1, in [6]).*

5. Conclusion

In this study, the evolutions of failure temperature and exposure duration of a P-CFRP as a function of mechanical load (in terms of the stress ratios varying from 0.1 to 0.68) have been investigated. With the stress ratio increase from 0.1 to 0.5, the P-CFRP failure temperature and exposure duration gradually reduces. Beyond this stress ratio, the thermal resistance of the studied P-CFRP significantly reduces. The experimental results also show that, under the stress ratio of 0.25, the rate of temperature increase has little influence to the failure temperature of the studied P-CFRP. When the stress ratio increases especially beyond 0.5, the failure mode of P-CFRP changes from soften mode to fragile mode due to the significant reduction in the range of failure temperature. Combined with the previous study on the same material, it can be inferred from this study that the loading order of elevated temperature and mechanical load has a small influence on performance of P-CFRP material. The thermal resistance of P-CFRP at different mechanical loads can be inferred from the evolution of mechanical resistance at different temperature levels. It is suggested that previous studies on the residual or thermo-mechanical performance of P-CFRP material under elevated temperature can be used for fire-concerned design or study with appropriate calibration❑

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