Behaviour of Carbon Fiber Reinforced Polymer (CFRP), with and without fire protection material, under combined elevated temperature and mechanical loading condition

Phi Long NGUYEN, Xuan Hong VU, Emmanuel FERRIER

Université de Lyon, Université Lyon 1, Laboratory of Composite Materials for Construction (LMC2), 82 bd Niels Bohr, F-69622 Villeurbanne, France. Mail: phi-long.nguyen@etu.univ-lyon1.fr, xuan-hong.vu@univ-lyon1.fr, emmanuel.ferrier@univ-lyon1.fr

ABSTRACT: In civil engineering, when a CFRP reinforced structure is subjected to fire, both structure and CFRP are simultaneously affected by elevated temperature and mechanical load. In Eurocode, the strengths of concrete and steel are described to be reduced with the rise of temperature while the performance of handmade carbon fiber reinforced polymer (H-CFRP) has not been identified and mentioned. This paper presents the thermo-mechanical performance of H-CFRP as different mechanical loading condition with and without thermal insulation. In the experimental test, the maximum temperature and duration, to which H-CFRP can expose, are identified at different levels of mechanical load. When the applied load increases, the rupture temperature and the exposure duration reduce. The rupture temperature of H-CFRP gradually decreases when the applied load increases from 10% to 50% of its ultimate strength of this material (at 20°C). As the applied load reaches 75% of the ultimate strength, the rupture temperature significantly reduces. Likewise, the exposure duration tends to gradually reduce when the applied load varies from 10% to 50% of its ultimate strength. This exposure duration considerably decreases when the applied load is equivalent to 75% of the H-CFRP ultimate strength. The tests carried out on H-CFRP, protected by insulation material, allow characterizing the actual effectiveness of the used insulation material on the performance of H-CFRP subjected to thermal and mechanical loading.

Keywords: carbon fiber reinforced polymer (CFRP), elevated temperature, thermomechanical behaviour, fire protective system

1 INTRODUCTION

In recent decades, there is an increase in the use of carbon fiber reinforced polymer (CFRP) in civil engineering for both reinforcing and retrofitting structures. With the advantages in high strength to weight ratio, corrosion resistance and fatigue, CFRP is employed to enhance strength, stiffness as well as ductility of concrete structures such as columns, beams and slabs. There are two major methods to exploit CFRP in civil engineering: by directly bonding laminate CFRP plate (or pultruded-CFRP / P-CFRP) on the surface of concrete structures using adhesive or by wrapping woven textile CFRP surrounding concrete structures with resin. The CFRP in the later method is hereby classified as in-situ CFRP or handmade CFRP (H-CFRP). Since the first application in the civil engineering, there is a tremendous demand concerning the working capability of CFRP in fire condition. Considerable researches have increasingly concentrated on the mechanical performance and properties of P-CFRP at elevated temperature. To the best of our knowledge, the performance of H-CFRP at similar condition is not yet studied. Over past decades, several researchers have focused on the evolution of tensile performance of P-CFRP following two popular procedures: in the first procedure, specimens were heated up to an predefined temperature, then mechanically tested until rupture following direct tensile test program (thermo-mechanical procedure); in the second procedure, after being heated up to predefined temperature and then cooled to ambient temperature, specimens were tested according to direct tensile test program at room temperature (residual procedure); Y.C. Wang et al performed a series of tensile test on P-CFRP at temperature ranging from 20°C to 600°C according to thermo-mechanical procedure, Wang et al 2007. The results showed that the tensile strength of P-CFRP reduced approximately 50% as the temperature increases up to 240°C and at 600°C, this strength reduced almost 90%. K. Wang et al measured the tensile strength of the P-CFRP strip according to thermo-mechanical procedure at temperature ranging from 22°C to 706°C, Wang et al 2011. The results demonstrated that tensile strength of the pultruded CFRP strip reduced approximately 50% at 350°C and more than 80% at 600°C. Foster et al observed the evolution of residual tensile properties of carbon-epoxy system from 20°C to 400°C, Foster et al 2005. The results displayed that residual strength of the material decreases about 20% at temperature up to 300°C, and about 80% at 400°C. Likewise, the tensile modulus varied less than 10% up to 400°C. Yu and Kodur studied the influence of temperature between 20°C to 600°C on the degradation of tensile properties of P-CFRP (strips and rods) according to thermo-mechanical procedure, Yu et al 2014. The results showed that tensile strength reduced about 50% (strips) and 40% (rods) at 300°C and roughly 90% (both strips and rods) at 600°C. On the other hand, the tensile modulus decreased about 30% (both strips and rods) of its value at 400°C and respectively 67% and 47% at 500°C for strips and rods. Cao et al tested the thermo-mechanical tensile strength of CFRP sheets with two different methods of loading control (by load increment and displacement one) at the temperature between 16°C and 200°C, Shenghu et al 2009. The results indicated that tensile strengths of CFRP sheets are significantly reduced with increasing temperature. From 16°C to 55°C, the tensile strength reduced approximately 30% and varied around this value up to 200°C. When subjected to the thermal load, most thermosetting resins and amorphous polymers show one major transition. This transition occurs in a narrow range of about several tens of degrees called glass transition temperature (Tg). With commercial products used in civil infrastructure applications, Tg varies between 50°C and 90°C, Foster et al 2008. When the temperature in the material reaches the transition temperature of the polymer matrix, the matrix becomes soften and the material's mechanical properties (Young's modulus, tensile strength) are significantly reduced. Therefore, the contribution of the matrix to the composite tensile strength gradually becomes negligible. This contribution reduces to zero after total decomposition of the matrix, characterized by a decomposition temperature Td (250-500°C), Mouritz et al 2006, Correia et al 2010. The matrix decomposition process usually releases heat, smoke, soot and toxic/combustible volatiles, Mouritz et al 2006. This possibly hastens the matrix decomposition itself, influences the mechanical properties of fiber and also hinders the deformation measurement. When a fire happens, structures are subjected to the heat and mechanical loads at the same time. In order to intensively observe the fire responses of structure, it is very important to measure mechanical load, temperature, deformation as they indicate the working status of structures. Therefore, the authors aim to study the performance of H-CFRP simultaneously exposed to elevated temperature and mechanical loading. In this paper, the authors present the evolution of maximum temperature and duration, to which H-CFRP can expose, when the applied mechanical load varies. A method to protect the H-CFRP using insulation material is also studied in this paper. The effect of the used insulation material is also evaluated and presented in the later parts.

2 EXPERIMENTAL WORK

This section presents experimental devices, specimens and experimental procedures that are used for this study.

2.1 *Experimental devices*

In this research, a thermo-mechanical testing system (Fig. 1) is used to study the thermo-mechanical behaviour of a H-CFRP material. The system including two main parts: the thermo-mechanical machine (called TM20kN-1200C) and laser extensometer. During the test, the TM20kN-1200C controls the force and temperature applied on the sample according to a determined procedure during while the laser extensometer allows measuring the elongation of CFRP specimen during the test and then calculating the tensile axial strain of CFRP sample, Nguyen et al 2016. The TM20kN-1200C includes a mechanical part (Fig. 1a) and a furnace (Fig. 1b). The mechanical part can perform direct tensile loading onto the testing specimen with loading capacity up to 20kN with programmable loading speed. The furnace is a cylinder oven that has external dimensions of 40 cm in height and 30 cm in diameter. The heating-chamber dimensions of this oven are 28 cm in height and 10 cm in diameter. This furnace can generate high temperature up to 1200°C with the maximum heating rate of 30°C/minute. The temperature level and the heating rate are programmable so that the testing system can auto-control the test with different target temperature levels and ramp rates. The furnace is insulated to guarantee that temperature of the closed system inside of the furnace is as the established one by testing program. There is a rectangular opening on the side of the furnace allowing two laser rays from the laser extensometer to measure the elongation of specimen. This opening can be closed in case the laser extensometer is unused. For measuring loading level, a force sensor is placed outside the furnace to measure as well as control the applied force. Six thermo-couples are placed inside the furnace including three on the wall of heating chamber and three on sample surface to follow real-time temperature and control the furnace during the test.

2.2 *Specimens*

In this research, the studied handmade CFRP is made from unidirectional woven carbon fibers added with polymer matrix (Fig. 2). According to data provided by supplier, the woven carbon fiber weights 310g/m2 and has the thickness of 0.32mm. The tensile strength of carbon fiber is =4902MPa and its tensile modulus is 230GPa. The elongation failure of carbon fiber is 2.1%. The minimum bond strength and shear strength of polymer matrix are 14MPa and 12 MPa respectively. The elastic modulus of polymer is 2GPa and its glass transition temperature is 40°C (supplier's data). The studied textile carbon fiber is first divided into tested size (includes 4 fiber tows) and aligned in flat surface. The polymer matrix is prepared by mixing two components of epoxy as the advised ratio and then swept on the textile. A waiting duration is needed to allow the polymer matrix harden to achieve its mechanical characteristics and well-bonded with the carbon fiber. In tensile test, the sample is normally placed in middle and their two ends are gripped by two clamps of the machine. Basically, the tensile axial force transmitted to the sample by the friction of the contacted regions between the clamps and the sample. However, the tensile strength of the tested material is much greater the friction force. Therefore, in order to effectively transmit the tensile force from the mechanic parts to the composite material, two aluminum plates are attached in each end by epoxy. The shear resistance and tensile resistance of the used epoxy are 15 MPa and 29.5MPa respectively. Fig. 3b shows the detailed dimension of the tested specimen (H-CFRP). The insulation that is used to protect the Handmade CFRP is a non-combustible material. As the supplier's data, its density is 0.458g/cm3; its compressive strength and bond strength are 0.893×10-3MPa and 8.012×10-

5MPa respectively. Accordingly to this data, its combustibility passes ASTM E136 and corrosion of steel passes ASTM E937.

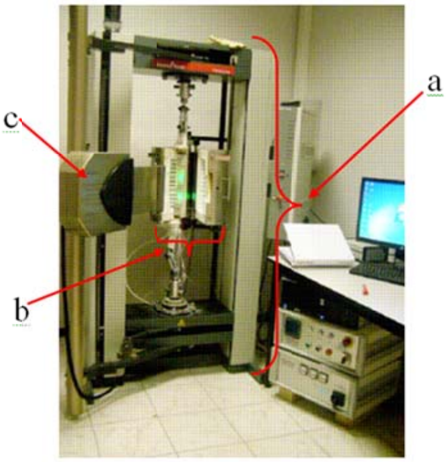

Fig. 1: Thermo-mechanical testing system

a: mechanical machine; b: furnace; c: laser extensometer

Fig. 2: Textile carbon fiber

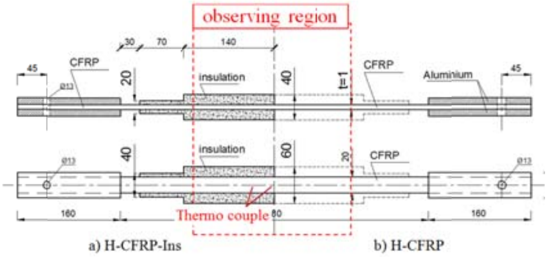

Fig. 3: Detail of sample

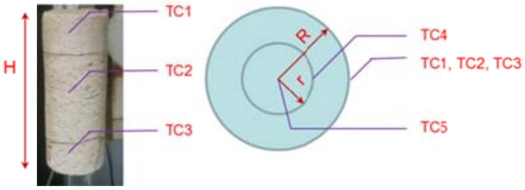

Fig. 4: Cylinder sample to test thermal resistance of insulation material, R=38mm, r=20mm , H=200mm with 5 positions of thermo-couple.

2.3 *Experimental procedures*

In this research, the H-CFRP will be tested following thermo-mechanical regimes (TM). The regime is to identify the rupture temperature corresponding to mechanical load that imposes on the material. In this regime, the specimen is first loaded with a force called applied force (F_w) in the first phase (Fig. 5). In the second phase, during while the F_w is maintained, the temperature surrounding the specimen increases with the programmed ramp rate at 30°C/minute from room temperature until rupture of specimen. The temperature, at which specimen is broken, is identified as rupture temperature (T_r) corresponding to the applied load level F_w. The maximum duration that the material can maintain its required performance is identified as exposure duration. The rupture temperature and exposure duration are two main factors which represent the thermo-mechanical performance of H-CFRP in the testing regime. The capacity to protect structure of the used insulation is first studied through a heat transfer test as described in Fig. 6 via a cylinder sample as described in Fig. 4. In this test, the temperature surrounding the sample will be increased with the heat rate 30°C/minute until reaching 1100°C. There are 5 thermo-couples (TC1 to TC5, Fig. 4) arranged inside and outside of the sample to study the heat transfer in the material during the test. The material is then applied to protect the H-CFRP (details as Fig. 3a) and tested following the thermo-mechanical testing regime (Fig. 5) to investigate the thermo-mechanical performance of insulated H-CFRP. The performance of H-CFRP and insulating protected H-CFRP is presented and discussed in the following sections.

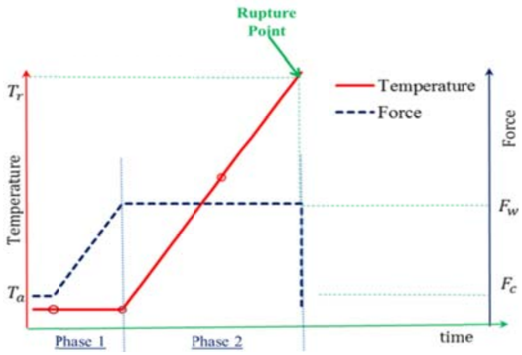

Fig. 5: Thermomechanical testing regime

Ta: ambient temperature; Tr: rupture temperature; Fc: control force; F_a: applied force

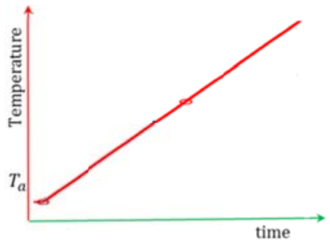

Fig. 6: Thermal test with isolant

3 RESULTS

Table 1 displays the ultimate strength and Young modulus of the studied handmade CFRP (H-CFRP) at room temperature. As can be seen in this table, the ultimate strength of H-CFRP is between 816 and 1001 MPa and the recorded Young modulus varies between 60.6-129.2 GPa. These values are 913.5 MPa and 85.9 GPa in averages. The identified value of ultimate strength is then used to identify the applied force that is applied on H-CFRP material in the thermo mechanical testing regime. Table 3 shows the thermo-mechanical performance of H-CFRP at different loading condition in terms of rupture temperature (T_rup, Table 3) and duration that H-CFRP can maintain its mechanical performance from the beginning until its rupture (exposure duration, Table 3).

Table 1: Properties of Handmade CFRP at room temperature

ID	Temperature	Ultimate stress	Young modulus
		MPa	GPa
C.20.a	20	922,8	129,2
C.20.b	20	816,5	60,6
C.20.c	20	1001,3	67,9
Average value		913,5	85,9

Table 2: Thermal-mechanical performance of Handmade CFRP with insulation results

Sample ID	Applied load ratio, f_w	T_rup		Exposure duration
		T_ex	T_in	
		°C	°C	minute
C.T.020.Ins	0,2	780	867	47,93
C.T.030.Ins	0,3	880	688	36,58

Table 3: Thermal-mechanical performance of Handmade CFRP for different applied load ratio

Sample ID	Applied load ratio, f_w	T_rup	Exposure duration
		°C	minute
C.T.010.a	0,1	630	31,2
C.T.010.b	0,1	629	32,7
C.T.010.c	0,1	650	36,8
C.T.025.a	0,25	578	23,7
C.T.025.b	0,25	598	25,7
C.T.025.c	0,25	613	20,1
C.T.050.a	0,5	543	52,1
C.T.050.b	0,5	540	22,5
C.T.075.a	0,75	46	0,4
C.T.075.b	0,75	45	0,4
C.T.075.c	0,75	64	2,2

The obtained results show that when the applied load ratio (f_w) is less than 0.5, the rupture temperature (T_rup) ranges between about 540°C to approximately 650°C whereas the exposure duration varies from 20 minutes to 52 minutes. When f_w is 0.75, the T_rup is low, between 45°C and 64°C, and exposure duration is less than 3 minutes. The obtained results with the H-CFRP samples protected with insulation material under the thermo-mechanical testing regime are presented in Table 2. The table shows the exterior and interior temperature of the insulation layer at the rupture point of H-CFRP and the exposure time that the material can maintain its performance. The obtained results include two cases of imposed load (0.2 and 0.3). The rupture temperatures in two loading case are 780°C and 880°C and the exposure durations are 48 minutes and 37 minutes respectively. Fig. 7 shows the evolution of temperature at three different positions from the exterior to the interior of the cylinder insulation material (Fig. 4). At the beginning of the test, the exterior temperature increases from initial condition with the ramp rate of 30°C/minute in about 30 minutes and reaches 900°C. Afterwards, this temperature keeps increasing with ramp rate 4°C/minute to reach about 1100°C in 50 minutes. The interior temperatures at thermo-couple 4 (TC4, T_in_1) and thermo-couple 5 (TC5, T_in_2) (Fig. 4) start to increase about 7 minutes to 14 minutes later than the exterior with ramp rate of 6.3°C/minute and of 8.9°C/minute respectively in the first phase. When the temperatures at TC4 and TC5 reach about 100°C, there are plateau phase in which the temperature slightly increases 1.3°C/minute and 0.4 °C/minute in about 13 minutes and 30 minutes correspondingly. In the final phase, the temperature at TC4 steeply increases with ramp rate of 23°C/minute while this rate at TC5 is 38°C/minute. Subsequently, these two temperatures reach 800°C in about 30 minutes and 20 minutes and the test is terminated due to safety condition when these temperatures reach 1029°C and 1007°C. Fig. 8 and Fig. 9 show the evolutions of temperature that are exterior and interior the insulation material layer during the thermo-mechanical test in two loading cases. When the applied load ratio is 0.2 (the corresponding imposed load is 2317N), the actual exterior temperature increases from room temperature (about 20°C) with the ramp rate is 28°C/minute and reaches 600°C in about 20 minutes (Fig. 8). Afterwards, the ramp rate decreases until the rupture of the H-CFRP. The evolution of the interior temperature also separates into three phases: in the first phase, the temperature gradually increases from initial temperature to 95°C with the ramp rate is 11°C/minute. This phase takes about 5 minus to complete. The interior temperature then slightly increases with the ramp rate of 0.65°C/minute in more than 10 minutes in the second phase before rapidly increases with the ramp rate is about 40°C/minute in the third phase. In the test with applied load ratio of 0.3 (correspond to imposed load at 3476N), the exterior temperature increases with the ramp rate of 24.5°C/minute and reaches 600°C in approximately 20 minutes (Fig. 9). The increase of the interior temperature also identified as three separate phases. In the first phase, the temperature takes about 5 minutes to gradually increase from initial temperature to about 94°C. The temperature then slightly increases with the ramp rate of 0.95°C/minute in about 15 minutes in the second phase before steeply rises at the ramp rate of 58°C/minute until ruptures.

4 DISCUSSION

According to obtained results, the rupture temperature of H-CFRP reduces as the applied load increases. Fig. 10 and Fig. 11 show the evolution of rupture temperature and thermal exposure duration of H-CFRP as the imposed load increases (C.T2 and C.T2.Avg, Fig. 10 and Fig. 11). When the applied load ratio increases from 0.1, 0.25 to 0.5, the rupture temperature gradually reduces from 636°C, 596°C to 541°C (in average) while the exposure duration varies from 33 minutes, 23 minutes and 37 minutes respectively. When the applied load ratio increases to 0.75, the rupture temperature significantly reduces to 52°C and the exposure duration drops to 1 minute (in average). The heat transfer test with insulation material shows that along the radius direction, the evolution of temperature is delayed and this impediment depends on the thickness of insulation layer (Fig. 7). The evolution of the interior temperature of the insulation material clearly separates into three identified phases. This has been confirmed by the tests with H-CFRP which is protected with studied insulation material.

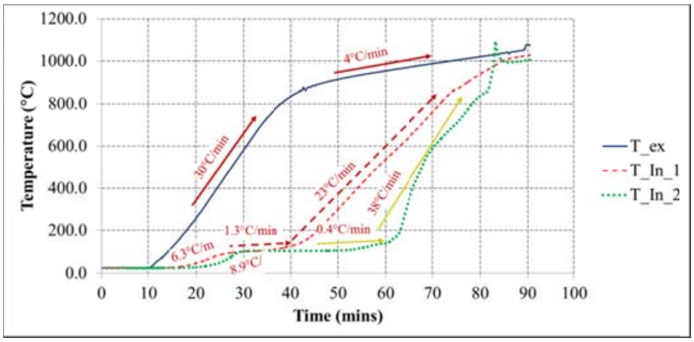

Fig. 7: Evolution of exterior (T_ex) and interior (T_in_1; T_in_2) temperatures of insulant during heat transfer test; Temperatures obtained with thermocouples TC1, TC2, TC3 (T_ex); TC4 (T_in_1); TC5 (T_in_2) (Fig. 4)

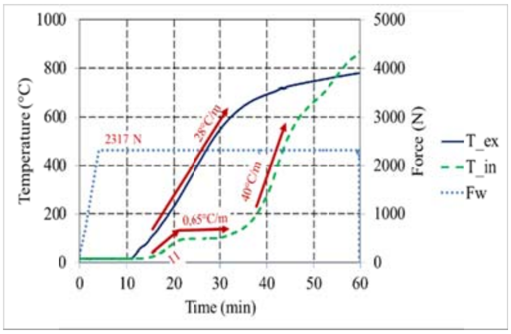

Fig. 8: Evolution of exterior and interior temperatures of H-CFRP with insulant at 20% of applied load ratio

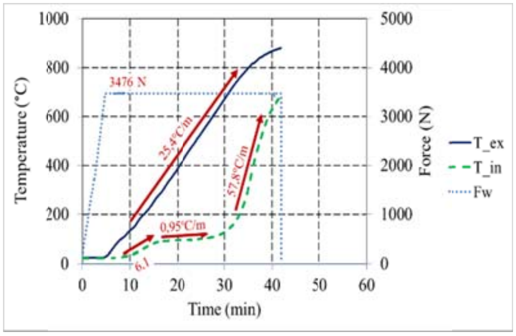

Fig. 9: Evolution of exterior and interior temperatures of H-CFRP with insulant at 30% of applied load ratio

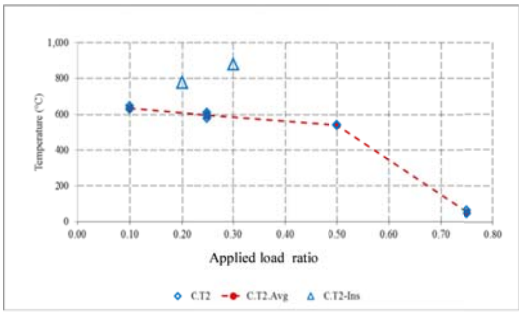

Fig. 10: Rupture temperature of H-CFRP at different applied load ratio

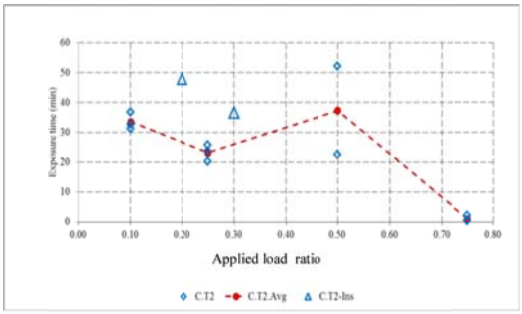

Fig. 11: Exposure temperature of H-CFRP at different applied load ratio

The result also shows that, the thermo-mechanical performance of H-CFRP protected with insulation material varies at different mechanical loading condition (C.T2-Ins, Fig. 10 and Fig. 11). Particularly, the exposed temperature of the H-CFRP can increase about 150°C at $f_w = 0.2$ and about 300°C at $f_w = 0.3$ (Fig. 10). Similarly, the exposure duration increases more than 20 minutes (f_w=0.2) and 15 minutes (f_w=0.3).

5 CONCLUSIONS

The aim of this work is to investigate the performance of H-CFRP at thermo-mechanical testing regimes and the improvement effect of this material when being protected with insulation material. It is clear that when the imposed load increases, the maximum temperature, that H-CFRP can be exposed to, decreases. When imposed load is less than 50% of its strength at 20°C, the variation of rupture temperature is small. When being imposed with load level that equals to 75% of its strength at 20°C, the rupture temperature of H-CFRP seriously decreases. The use of insulation material can improve the thermo-mechanical performance of H-CFRP in the tested regime. The thermal-detent capacity depends on the thickness of the used insulation material layer. With of 2cm thickness of the used insulation material, the heat penetration is impeded and the temperature on H-CFRP surface retards about 10 minutes. In the employed testing regime, the H-CFRP protected with insulation material can expose to higher temperature and in longer duration.

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