



Evaluating the high-temperature endurance of FRP-strengthened concrete using an innovative insulation system: Experimental investigation

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ABSTRACT

Extensive research on fiber-reinforced polymer (FRP) composites has led to the presumption that this material is an effective solution for repairing and strengthening the reinforced concrete (RC) elements. The use of FRP significantly enhances the carrying capacity of elements under structural loads. However, the poor fire performance of this material poses a major concern, particularly in buildings. High temperature exposure can damage the adhesive bonding of polymer matrices and degrade their strength. Therefore, the use of thermal insulation is essential to ensure the safety of FRP-strengthened buildings. This study experimentally investigated the effectiveness of a recently developed thermal insulation system, “DYMAT® FIREWRAP”, in protecting the carbon and glass FRP wrapped concrete specimens. The tested insulation system comprised two different materials namely DYMAT® RS and Dymatherm. During the experiments, 50 concrete specimens with different strengthening and insulation configurations were prepared and exposed to high temperatures of 200 °C and 400 °C. The results highlight the importance of using thermal insulation on FRP repaired concrete elements. After high temperature exposure of 200 °C, the compressive strength losses of CFRP wrapped specimens were 12% lower than those of the non-insulated specimens. For GFRP strengthened specimens, the strength loss was 17% less than that for the non-insulated specimens. After high temperature exposure of 400 °C, the CFRP wrapped specimens experienced 27% less reduction in their compressive strength, and the strength loss for GFRP wrapped specimens was reduced by 32%. Among the considered configurations, the presence of the RS material as an inner layer played a major role in protecting the epoxy from deterioration. Dymatherm provided adequate protection; however, the number of layers did not significantly affect the high temperature endurance of the specimens.

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1. Introduction

Over the past two decades, extensive research on fiber-reinforced polymer (FRP) composites has led to the presumption of that material is an effective solution for retrofitting and strengthening the reinforced concrete (RC) elements [1–3]. The high specific strength, low weight, and high durability of FRP composites render them suitable for construction projects [4,5]. Factors such as higher tensile strength and corrosion resistance make FRP advantageous over traditional reinforcing materials [6,7]. Although FRP has a higher initial cost, its lower lifecycle cost makes it a more cost-efficient solution than other retrofitting materials such as steel [8,9]. Due to conditions such as aging or lack of constant maintenance of structural elements, it is essential to upgrade these elements and enhance their carrying capacities [10]. Extreme loading conditions, such as earthquakes and fires, may result in the removal of some structural elements; therefore, other elements must act as substitutional elements with carrying capacities higher than their design values.

Numerous efforts have led to the development of different types of FRP composites with specific characteristics such as carbon FRP (CFRP), glass FRP (GFRP), aramid FRP (AFRP), unidirectional or bidirectional FRPs, each possessing unique characteristics suited for different purposes. Among the different types of FRP, CFRP provides higher tensile strength [11,12], whereas GFRP has lower thermal conductivity and offers comparatively better insulation [13,14]. Despite their many advantages, FRP composites exhibit poor fire performance, which poses a major concern from a fire safety perspective [15,16]. The matrix part, which is responsible for stress distribution among the fibers, has the highest sensitivity to high temperatures. This is due to the very low glass transition temperature (T_g) between 65 °C and 120 °C [11,17,18]. Exposure to high temperatures leads to severe damage to the matrix and integrity of the composite [19]. The bonding between FRP and strengthened elements is crucial for the structural behavior of the element. Fire exposure deteriorates the mechanical properties of the FRP, which affects the bonding between the element and FRP [10,20]. Therefore, to use FRP composites for structural strengthening purposes, it is important to satisfy the fire safety requirements. In this regard, many research works have used analytical and numerical methods to determine the fire performance of FRP strengthened RC elements under different loading conditions [21–33].

Due to their time, cost, and energy efficiency, numerical analyses have been widely adopted in existing research on the fire performance of FRP-strengthened RC elements. However, numerical analysis cannot fully model the real fire behavior of elements affected by multiple environmental factors. In addition, the experimental evaluation offers a more realistic representation of fire effect over elements. Thus, scholars have attempted to replicate the high temperature performance of FRP-strengthened members using experimental methods. Yoo and Choo [34] have experimentally evaluated the properties of CFRP compression bars in RC columns and the effects of high temperature exposure on their structural performance. They fabricated 24 short columns reinforced with CFRP or steel bars and exposed the columns to different temperature levels (0, 150, 300 and 450 °C). After the high temperature exposures, using concentric axial loading and standard-based analytical results, the structural performance of the columns was evaluated. The results indicate that for temperatures less than 450 °C, the stress-strain curves of the CFRP bars exhibited nearly linear behavior. It was also observed that until the temperature reached 150 °C, the compressive strength of CFRP reinforced columns was improved. However, exposure to higher temperatures decreased this property, and temperature exposures of 450 °C reduced their compressive strength by more than 50%. Al-Salloum et al. [35] presented the results of a two-phase experimental study on high temperature performance of FRP strengthened concrete specimens. They used CFRP and GFRP fabrics to strengthen the cylinders that were exposed to two different high temperatures of 100 °C and 200 °C for three different exposure durations of 1, 2, and 3 h. After high temperature tests, the specimens were subjected to uniaxial compression tests to measure the high temperature performance of the strengthened specimens. Their results demonstrated the high temperature vulnerability of externally bonded FRP specimens, and the experienced strength losses were significantly affected by the rate of the temperature rise. Similarly, some experimental studies were focused on the behavior of various FRP strengthened specimens under different high temperature exposure conditions [36–41].

From a variety of studies, it is well established that the high-temperature performance of FRP-strengthened elements must be improved. Therefore, several attempts have been made to identify appropriate materials for improving the high-temperature performance of FRP-strengthened elements. In 2000, Blontrock et al. [42] conducted an experimental study on RC beams strengthened with CFRP to evaluate the effect of fire on the bonding between FRP and concrete. They observed that applying thermal insulation to FRP-strengthened elements is essential to decrease the fire-induced losses in the mechanical properties of FRP. Barnes and Fidell [43] also focused on the effectiveness of insulation on the scaled RC beams strengthened with CFRP. They used 1 h of standard fire for temperature exposure and 4-point loading for the post fire bending load test. They observed that after exceeding T_g and deterioration of the bond between FRP and RC element, CFRP loses its workability and cannot provide extra support for stress bearing of the element. Their results indicated that thermal insulation with a thickness of 15–20 mm can only protect the element for approximately 30–45 min of fire. Ahmed and Kodur [44] have constructed four RC beams to evaluate the fire performance of CFRP strengthened beams insulated with Tyfo® WR Advanced Fire Protection. Their results highlighted the effectiveness of the insulation system considered for fire failure prevention. It also highlighted the importance of employing proper insulation schemes to prevent the debonding of the FRP. In 2012 Palmieri et al. [45] conducted an experimental study on FRP strengthened RC beams and employed 5 different fire insulation schemes to obtain the performance of the strengthened beams under both fire and service loads. They observed that the insulation could perfectly protect the beams for 2 h and none of the insulated beams experienced a failure. Their results point out that a proper insulation scheme can significantly increase the fire performance of the FRP strengthened RC beams. Ji et al. [46] experimentally evaluated the fire performance of nanocomposite coatings on FRP strengthening systems. They first subjected the constructed RC beams to 3-point loadings and later used FRP and coating to repair the damaged beams. The repaired specimens were subjected to 10 min of fire load and the post fire residual strength of the specimens was obtained. Their results highlighted the effectiveness of the

new repair system in increasing the bonding strength. They also observe that using fire retardant along with nanocomposites can improve the strength and fire response of the repaired beams.

In 2014, Yu and Kodur [47] focused on the fire performance of the near-surface mounted (NSM) FRP reinforcing on RC T-beams. They have constructed 4 CFRP strengthened RC beams and subjected them to fire and service loads. Their results show that using NSM FRP without any external insulation can perfectly protect the specimens for up to 3 h of the fire. Seo et al. [48] have also evaluated the high temperature performance of externally bonded and NSM-FRP concrete blocks that were fire insulated using calcium silicate boards. They observed that despite using the same insulation, NSM blocks demonstrated better fire resistance than externally bonded blocks. Their results indicated that to provide adequate fire protection, an insulation board must be applied on the sides and face of the FRP. Moreover, they performed a finite element analysis to estimate the temperature variation in epoxy and observed that side insulation along with face insulation can prevent the epoxy from reaching its critical temperature.

Guruprasad and Ramaswamy [49] used experimental and numerical methods to investigate the effectiveness of geopolymer mortar and simwool ceramic fiber blankets as insulating materials on the high-temperature performance of CFRP-strengthened concrete cylinders. In their parametric study, they evaluated the effects of two different exposure durations and four different insulation thicknesses. From the results it was observed that the utilized insulations could adequately protect the specimens from high temperature exposure of 715 °C for 2 h. It was also observed that under considered exposure temperatures and durations, a 90 mm of the utilized insulating material can provide the required protection and it is not recommended to further increase the insulation thickness. Imran and Mahendran [50] performed a two-phase experimental analysis on FRP-strengthened short steel columns under fire and axial compression loads and investigated the effectiveness of spray-applied thermal insulation. Initially, the CFRP strengthened short columns were subjected to fire and axial compression loads and observed that after 225 °C CFRP completely lose its properties. In the second stage, the CFRP-strengthened steel column was thermally insulated and subjected to the same loading conditions. It was observed that the utilized insulating material could improve the performance of the strengthened columns for up to 60 min of standard fire exposure. Recently in 2022, Sobia et al. [10] fabricated full scale RC columns and evaluated the effects of using insulation on the performance of CFRP strengthened RC columns. They observed that employing ultra-high performance fiber reinforced cement composite as insulation material can slow down the failure time of the specimens by 15 min.

These studies have significantly contributed to improving the fire performance of FRP strengthening systems by proposing new insulating materials or advancing existing materials. Since the performance of the fire insulations is significantly affected by their compositions, altering their composition can result in a substantial change in their performance [51]. Moreover, existing insulation materials have drawbacks such as thickness, aesthetic appearance, and the additional dead load imposed on the structures, which hinder their optimal performance [52]. Hence, further research on thermal insulation can lead to the development of a more comprehensive solution for protecting FRPs from high temperatures and identifying the optimal configuration to improve their thermal protection properties, thus ensuring the longevity of FRP strengthened concrete structures. In addition, the conducted experiments were mostly focused on the fire performance of CFRP, and only a few studies have compared the effectiveness of insulation in enhancing the fire performance of different types of FRP simultaneously.

Accordingly, this study aimed at evaluating the fire performance of CFRP and GFRP strengthening systems insulated with the recently developed fire protection system DYMAT® FIREWRAP, which consists of DYMAT® RS and Dymatherm. The DYMAT® RS is a thin reddish fabric made of silica composite with high strength and high resistance to elevated temperature. Dymatherm is a ceramic blanket with a felt-like texture that comprises high temperature long fibers. The insulating materials of the system are durable solid sheets that make them advantageous over spray applied gypsum and similar insulating materials that can deteriorate over time and under extreme weather exposure. To investigate the effectiveness of the system on high temperature performance of CFRP and GFRP strengthened concrete a total of 50 cylindrical RC specimens were fabricated. From these, 5 specimens were used as reference specimens and 45 of them were strengthened with CFRP or GFRP composites. To provide thermal protection, different combinations of DYMAT® RS and Dymatherm were applied on FRP surfaces.

Since the insulation thickness is an important factor affecting the performance of thermally insulated FRP-strengthened specimens [52], the specimens were insulated with different configurations and thicknesses to determine the optimum configuration that trades off between performance and thickness. Thus, the specimens were insulated with four different combinations and exposed to temperatures of 200 °C and 400 °C. After the temperature tests, the specimens were subjected to uniaxial compression tests to determine their residual compressive strengths and to evaluate the effectiveness of each insulation scheme.

2. Materials and methods

These tests aimed to determine the effectiveness of FIREWRAP insulation system comprising DYMAT® RS and Dymatherm with different schemes on thermal resistance and strength loss of FRP materials exposed to high temperatures (200 °C and 400 °C). Based on the results obtained from temperature measurements, the uniaxial compression test of samples, and the subsequent changes in their performance, the effectiveness of 4 insulation schemes were evaluated.

To conduct these experiments, cylindrical concrete samples were fabricated in the laboratory. Some of these fabricated samples were selected as reference samples, and the rest were divided into two equal parts; samples from the first part were wrapped using CFRP, and specimens from the second part were wrapped with GFRP. All FRP composites and insulation materials were manufactured by DYMAT® company. The CFRP and GFRP composites used in this experimental phase were DYMAT® DHC-190 carbon and DYMAT® DHE-272 glass fibers, as well as a two-part room temperature cure DYMAT® D epoxy resin. The naming convention for samples was done with respect to the parameters considered in this set of the experiment (temperature level, fiber polymer fabric type, and insulation methods) which are presented in Table 1.

Table 1

Overview of test samples and their naming.

Set-1 (CFRP)			Set-2 (GFRP)		
	Test 1	Test 2		Test 3	Test 4
20 °C	400 °C	200 °C	20 °C	200 °C	400 °C
Ref. Set-1 (1)	CFRP-400 (1)	CFRP-200 (1)	Ref. Set-2 (1)	GFRP-200 (1)	GFRP-400 (1)
Ref. Set-1 (2)	CFRP-400 (2)	CFRP-200 (2)	Ref. Set-2 (2)	GFRP-200 (2)	GFRP-400 (2)
CFRP (1)	CFRP-T1-400 (1)	CFRP-T1-200 (1)	GFRP (1)	GFRP-T1-200 (1)	GFRP-T1-400 (1)
CFRP (2)	CFRP-T1-400 (2)	CFRP-T1-200 (2)	GFRP (2)	GFRP-T1-200 (2)	GFRP-T1-400 (2)
	CFRP-T2-400 (1)	CFRP-T2-200 (1)		GFRP-T2-200 (1)	GFRP-T2-400 (1)
	CFRP-T2-400 (2)	CFRP-T2-200 (2)		GFRP-T2-200 (2)	GFRP-T2-400 (2)
	CFRP-T3-400 (1)	CFRP-T3-200 (1)		GFRP-T3-200 (1)	GFRP-T3-400 (1)
	CFRP-T3-400 (2)	CFRP-T3-200 (2)		GFRP-T3-200 (2)	GFRP-T3-400 (2)
	CFRP-T4-400 (1)	CFRP-T4-200 (1)		GFRP-T4-200 (1)	GFRP-T4-400 (1)
	CFRP-T4-400 (2)	CFRP-T4-200 (2)		GFRP-T4-200 (2)	GFRP-T4-400 (2)

T: Insulation type.

As demonstrated in Table 1, a total of 4 temperature tests, comprised two different types of fiber polymer fabrics and two different temperature ranges. To reduce the possibility of experimental errors, two samples were tested for each unique parametric configuration [35,40,53,54]. So, each temperature test was conducted on 10 specimens separately. After temperature tests, all specimens were subjected to compression tests. The details of the performed experiments are described in the following sections.

2.1. Fabrication of test specimens

Two different sets of specimens were fabricated for FRP strengthening with carbon and glass fibers (Fig. 1). All cylindrical specimens were constructed with a height of 450 mm and diameter of 20 mm. Concrete was produced according to the procedure specified in BS EN 206 [55]. The concrete mix utilized for fabrication comprised type CEM I 42.5 R cement with the specifications listed in Table 2, 45% coarse aggregate and 55% fine aggregate by weight, and the specific gravities of the fine and coarse aggregates used in the concrete mixture were 2.62 and 2.70, respectively. The mix proportions of the concrete are listed in Table 3. The concrete was compacted using a vertical immersion vibrator fitted with a high-frequency electric motor, based on a two-stage compaction method. After 24 h of casting, the concrete specimens were demolded and placed in a curing tank at 20 ± 2 °C for 28 days.

While pouring concrete for each set, 6 standard cube samples were also cast. After removing concrete specimens from the curing tank, all samples were subjected to uniaxial compression tests. The average compressive strength of samples from Set-1 and Set-2 were determined as 24.64 MPa and 22.94 MPa, respectively.

2.2. Strengthening procedure

Before applying FRP, the surfaces of the specimens were fully dried. All constructed specimens, except the reference samples, were wrapped using fiber polymer composites. The age of the concrete at the time of CFRP and GFRP wrapping was 32 days. Set-1 specimens were wrapped using CFRP and Set-2 specimens were GFRP wrapped. In both sets, 2 plies of FRP were wrapped and an overlap length of 200 mm has been considered. The epoxy matrix is comprised of epoxy resin and hardener. In all mixes, the weight of resin and fabric were equal while for resin and hardener, a mixing ratio of 1:3 has been used. After applying the FRPs, all specimens had 7 days of waiting time in the laboratory environment as the curing time for the epoxy. The strengthening procedures are depicted in Figs. 2–5. The summary of the properties of the utilized fibers and epoxy is presented in Table 4.

2.3. Insulation types and their application

The FIREWRAP is a composite fire protection system that is designed to withstand various harsh environmental conditions and can be tailored to different geometries. So, it can provide long-term protection for the structures that are subjected to cyclic temperature loadings and elements with irregular shapes. The system comprises two different materials namely DYMAT® RS and Dymatherm. DYMAT® RS is a 1.0 mm thick high-temperature resistance cloth. Dymatherm is a textured blanket insulator with a nominal thickness of 1.5 cm. Both materials are good insulators, and their negligible thickness makes the system a suitable candidate for a fire protection system. To precisely evaluate the effectiveness of the FIREWRAP insulation system, 4 different combinations of these materials (T1, T2, T3, and T4) were considered. The insulation materials were just wrapped around the specimens and no adhesive was used. After applying insulations, an iron wire was used to hold the layers together. Details of the layer configuration for different insulation types are depicted in Table 5 and the stages of insulating the specimens are shown in Figs. 6 and 7.

2.4. Temperature tests and measurements

The test specimens were placed on the car-bottom of the furnace and were prepared for temperature test and, ceramic thermal insulation caps were used to cover the top surface of the insulated specimens. This was done to prevent direct temperature exposure to the non-insulated top surface of the specimens and increase the precision of the performed evaluations. In each test, thermocouples were attached to the FRP surface of the insulated specimens to monitor the temperature development at these points. Arrangements of the specimens in the furnace and thermocouple measurement points on the insulated specimens are demonstrated in Fig. 8.



Fig. 1. Constructed specimens.

For the temperature tests, two different time-temperature protocols have been used (Fig. 9). In these protocols, the temperature is rising with a heating rate of $2.5\text{ }^{\circ}\text{C}/\text{min}$ until the interior temperature of the furnace reaches $200\text{ }^{\circ}\text{C}$, for the first protocol, and reaches $400\text{ }^{\circ}\text{C}$ for the second protocol. Then remains constant and continues with these values for 1 h. For Protocol-1 it took 134 min, and for Protocol-2 it took 214 min, to reach their maximum temperature. Selection of the heating rate and duration of the constant temperature exposure was selected with respect to the existing literature [56–61].

Upon completion of the temperature test, the furnace door was opened, and using a pyrometer, the surface temperature of each layer of the specimens was measured. After temperature measurements, the samples were placed outside the furnace and cooled down to room temperature. The mentioned procedures are illustrated in Figs. 10 and 11.

2.5. Uniaxial compression tests

After the cooling down period, a servo-hydraulic compression testing machine with 3000 kN capacity was used to perform the uniaxial compression test on the specimens. All samples were tested with the same loading rate of 0.6 MPa/s [62,63]. Uniaxial compression tests for these specimens were started after 60 days of pouring the concrete.

Table 2
Chemical, physical and mechanical properties of cement.

Chemical Composition		Physical and Mechanical Properties	
Components	(%)	Retained on Sieve 45 μm (%)	9.80
SiO ₂	19.46	Retained on Sieve 90 μm (%)	1.00
Al ₂ O ₃	5.11	Specific Surface (Blaine) (m ² /kg)	412.60
Fe ₂ O ₃	3.31	Specific Gravity	3.12
CaO	60.23	Setting Times (Vicat) (min)	Initial 140
MgO	2.08		Final 200
SO ₃	3.05	Water Demand (%)	29.20
Na ₂ O	0.27	Soundness (mm)	1.00
K ₂ O	0.69	Compressive Strength (MPa)	2-day 28.00
Cl ⁻	0.02		7-day 40.40
Loss on Ignition (LOI)	3.00		28-day 51.50

Table 3
Mix proportions of concrete.

w/c Ratio	Unit Weight (kg/m ³)			
	Cement	Water	Coarse Aggregate	Fine Aggregate
0.60	300	180	823.50	1006.50



Fig. 2. Preparation of FRP

3. Results and discussions

3.1. Temperature tests

Consistent with the literature [64], during the 400 °C temperature tests, the non-insulated FRP specimens generated significant smoke; therefore, the ventilation system of the furnace was activated (Fig. 12). During the temperature tests, the data collected using the data logger were processed and transformed into graphs. Using these data, the effectiveness of each insulation method is evaluated. The obtained temperature data are shown in Figs. 13 and 14.

Temperature evaluation has been conducted based on the maximum temperature values. The key findings of the performed temperature measurements from each test are detailed below.

- After temperature exposure of 400 °C it was observed that the epoxy of the specimens without an inner layer of RS deteriorated and the Dymatherm layer adhered to the surface of the FRP layer. In 200 °C temperature tests, insulation materials could protect the layers and the epoxy resin was not deteriorated (Fig. 15).



Fig. 3. Preparation of epoxy matrix (epoxy resin and its hardener).



a) CFRP



b) GFRP

Fig. 4. Stages of wrapping applications.

- After 400 °C temperature exposure, the outermost RS material layer of the samples deteriorated, and its surface was exfoliated (Fig. 16).

3.1.1.1. Test 1: Set-1 CFRP 400 °C

- As it was expected, within insulated samples, the lowest CFRP surface temperature after 214 min of temperature test was obtained from the T4 insulation method (50 °C). Also, the maximum CFRP surface temperature of the insulated samples was 125 °C (Fig. 14-a).



a) CFRP



b) GFRP

Fig. 5. FRP wrapped specimens.

Table 4

Characteristics of the employed strengthening materials.

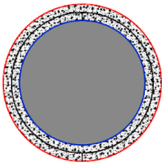
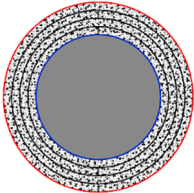
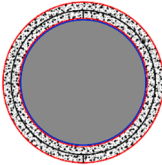
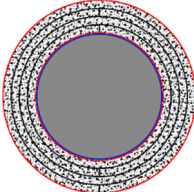
	Fibers	
	DYMAT® Carbon Fiber System DHC-190	DYMAT® Glass Fiber System DHE-272
Tensile Strength (GPa)	4.83	3.73
Tensile Modulus (GPa)	280.0	83.3
Ultimate Elongation (%)	1.65	4.50
Density (g/cm ³)	1.74	2.55
Weight (g/m ²)	644	922
Fiber Thickness (mm)	0.37	0.36
2-Part Epoxy		
Tensile Strength (MPa)	90.0	
Shear Modulus (GPa)	5.0	

- It was observed that using RS material in the inner layer of insulation plays an important role in the thermal protection of CFRP materials. From Table 6, it can be seen that the absence of this layer, either 2 or 4 layers of Dymatherm (T1 and T2) did not make significant differences in the surface temperature values of FRP at the end of the temperature test (3–6 °C).
- When RS material was used in the inner layer (T3 and T4), in the samples with more layers of Dymatherm, the CFRP surface temperature was lowered by 53 °C at the end of the test. Besides, this layer prevented Dymatherm from sticking to the CFRP surface at the end of the heating process (Table 6).
- In samples with 2 layers of Dymatherm, utilizing RS material in the inner layer (T1 and T3) resulted in an average difference of 28 °C in the measured CFRP surface temperature. In the samples with 4 layers of Dymatherm (T2 and T4), this difference is around 43 °C (Table 6).

3.1.2. Test 2: Set-1 CFRP 200 °C

- Contrary to expectation, within insulated samples, the lowest CFRP surface temperature after 134 min of temperature test was obtained from the T3 model (32 °C), not from the T4. However, the observed differences between T3 and two measured values from T4 models (34 °C and 35 °C) were not significant. The maximum CFRP surface temperature measured from insulated samples was 55 °C (Fig. 14-b).
- For cases with no inner layer of RS material, either 2 or 4 layers of Dymatherm (T1 and T2) did not make significant differences in the surface temperature values of CFRP at the end of the test (1–16 °C). When RS material was used in the inner layer (T3 and T4), in cases with more layers of Dymatherm, the CFRP surface temperature was lowered by 16 °C (Table 6).
- In samples with 2 layers of Dymatherm, the use of RS material in the inner layer (T1 and T3) resulted in an average difference of 5 °C in the measured CFRP surface temperature at the end of the temperature test. In cases with 4 layers of Dymatherm (T2 and T4), this difference is around 4 °C (Table 6).

Table 5
Insulation configurations.

Insulation Type ID	Configuration Information			Schematization	Insulated Specimens
	DYMAT® RS (inner)	DYMAT® Dymatherm	DYMAT® RS (outer)		
T1	×	2 plies	✓		
T2	×	4 plies	✓		
T3	✓	2 plies	✓		
T4	✓	4 plies	✓		

- Evaluating the results obtained from the 200 °C temperature test, demonstrate that the existence of RS material in the inner layer caused no difference in the surface temperature of CFRP. It was also observed that more layers of Dymatherm had a negligible effect on this surface temperature value.

3.1.3. Test 3: Set-2 GFRP 200 °C

- As it was expected, within insulated samples, the lowest GFRP surface temperature after 214 min of temperature test was obtained from the T4 insulation method (41 °C). Moreover, the maximum GFRP surface temperature of the insulated samples was 65 °C (Fig. 14-c).
- For cases with no inner layer of RS material, either 2 or 4 layers of Dymatherm (T1 and T2) did not make significant differences in the surface temperature values of FRP at the end of the temperature test (2–17 °C). When RS material was used in the inner layer (T3 and T4), more Dymatherm layers, caused an average decrease of 12 °C in the measured surface temperature of GFRP (Table 6).
- In the T1 and T3 model, which are wrapped with and without RS material in their inner layer, an average difference of 7 °C was observed in the surface temperature of GFRP. It was also observed that using 4 layers of Dymatherm (T2 and T4) does not affect this temperature value (Table 6).
- Evaluating the results obtained from the 200 °C temperature test, demonstrate that the existence of RS material in the inner layer, and having more layers of Dymatherm does not affect the surface temperature of GFRP.

3.1.4. Test 4: Set-2 GFRP 400 °C

- Contrary to expectation, within insulated samples, the lowest GFRP surface temperature after 214 min of temperature test was obtained from the T2 within insulated samples (64 °C), not from T4. The temperature values measured from the models with the T4 insulation method were 80 °C and 98 °C. A possible explanation for this might be that in the T2 insulation method

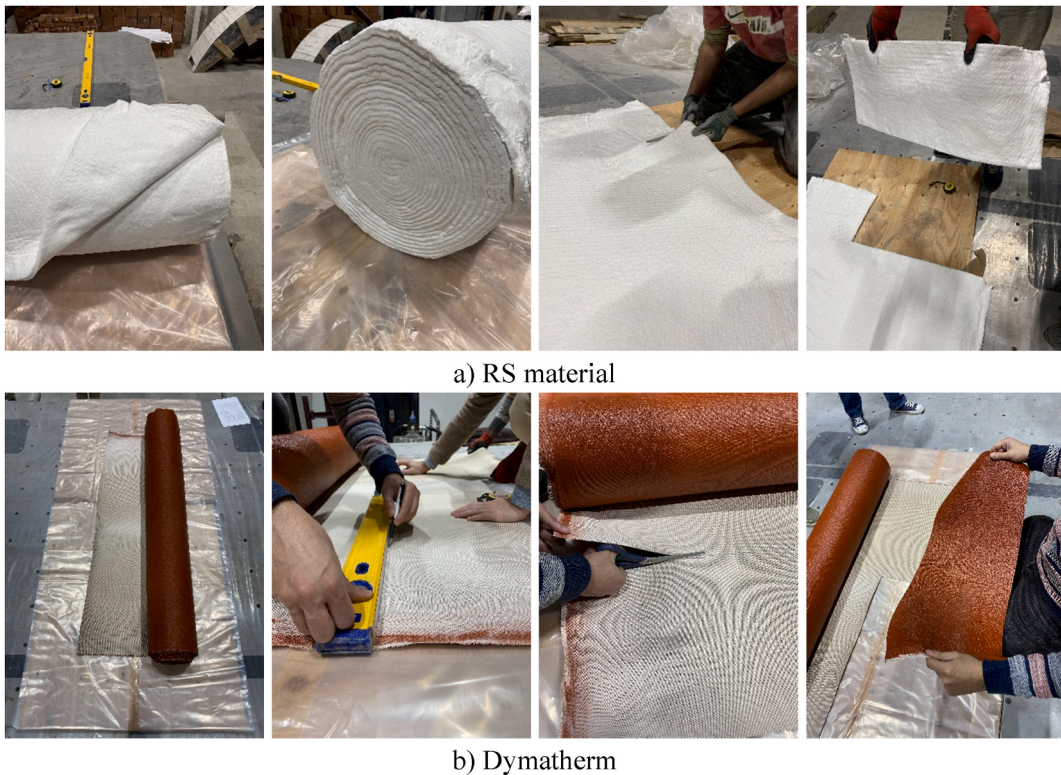


Fig. 6. Preparation stages of the insulation materials.

thermocouples were placed in a comparatively deeper location. The maximum surface temperature of GFRP for insulated samples was 174 °C (Fig. 14-d).

- It was observed that in the tests with maximum temperature of 400 °C, the use of RS material in the inner layer plays an important role in the thermal protection of GFRP materials. For cases with no RS layer, and 2 or 4 layers of Dymatherm (T1 and T2), there was an average difference of 63 °C in the surface temperature of FRP at the end of the temperature test. When RS material was used in the inner layer (T3 and T4), along with more layers of Dymatherm, the GFRP surface temperature was decreased by 27 °C (Table 6). Also, this layer prevented the sticking of Dymatherm to the GFRP surface at the end of the test.
- In samples with 2 layers of Dymatherm, utilizing RS material in the inner layer (T1 and T3), made an average difference of 35 °C in the measured GFRP surface temperature at the end of the temperature test. In the samples with 4 layers of Dymatherm (T2 and T4), this difference is around 24 °C (Table 6).

3.2. Compression tests

To evaluate the performance of each configuration, the strength values obtained after the temperature tests were compared with those of the reference samples. The strength values, maximum temperatures obtained from the FRP/insulation interface, and comparison between strength losses are presented in Tables 7–9. The typical failure modes obtained from the pre- and post-compression tests of the specimens are shown in Figs. 17 and 18, and the residual strengths of the specimens are compared in Fig. 19.

3.2.1. Set-1 (CFRP/200 °C (test 2) and 400 °C (test 1))

- In this set of experiments, all FRP wrapped models as well as reference models were subjected to uniaxial compression tests. In the tests conducted for Set-1, the average compressive strength of the reference specimens was measured as 21.42 MPa, while this value reached 55.58 MPa after applying CFRP to the specimens.
- Exposing the models of Set-1 to high temperatures decreased their compressive strengths. After exposing Test 2 specimens to Protocol-1 (200 °C), the compressive strength of the samples with no insulation reached 43.68 MPa and experienced the most strength loss. Exposing Test 1 specimens to Protocol-2 (400 °C) caused more decreases in their compressive strength. The strength of the model with no insulation decreased significantly and reached 27.85 MPa.
- In the T1 and T2 models, the number of Dymatherm layers did not affect the changes in the compressive strength at both 200 °C and 400 °C. Similar results were obtained for the T3 and T4 models.
- After 400 °C exposures, the decrease in compressive strength of the insulated specimens with an inner layer of RS material was 7–10% less than the specimens without an inner layer of RS material.



Fig. 7. Wrapping applications of the insulation layers.

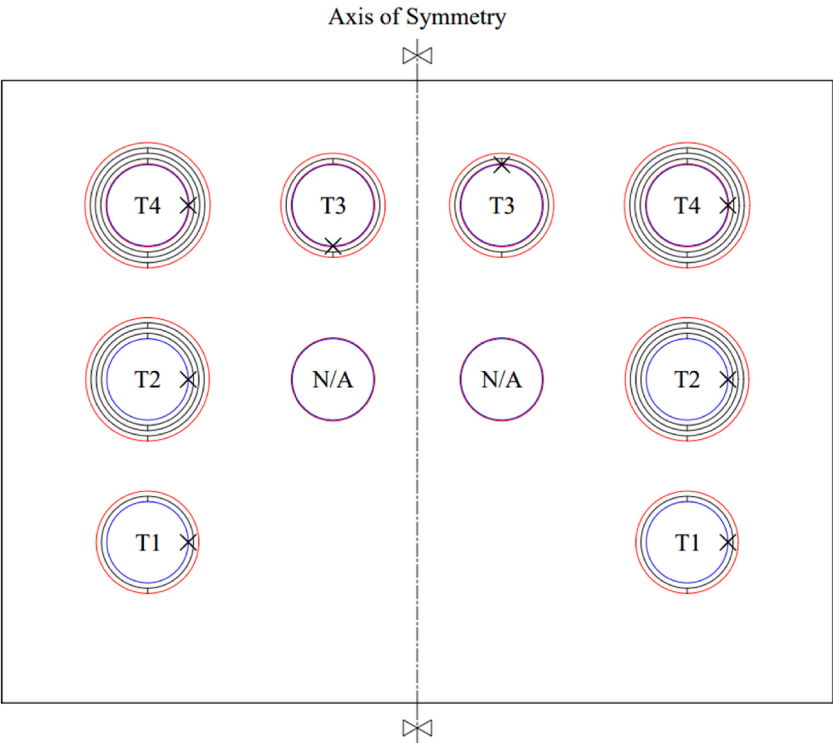


Fig. 8. Placement of samples in the furnace and location of measurement points.

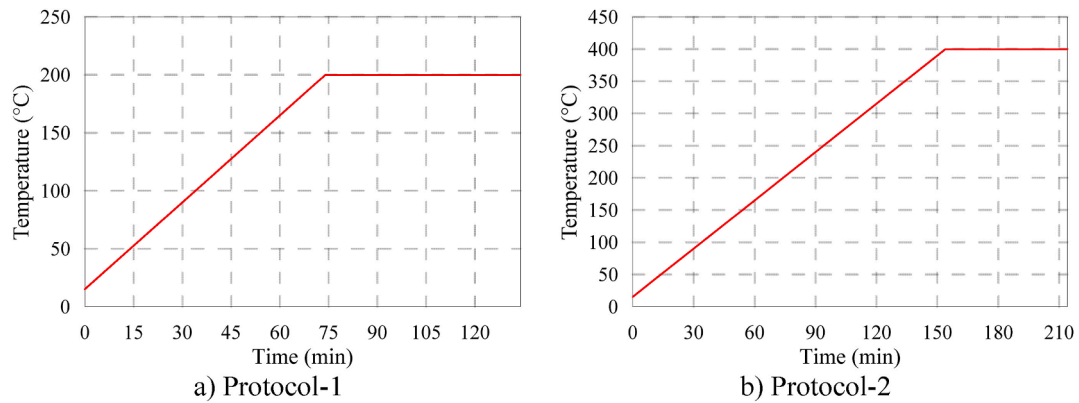


Fig. 9. Furnace interior temperatures during the tests.

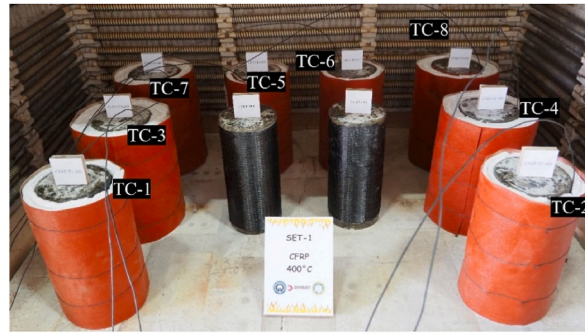
3.2.2. Set-2 (GFRP/200 °C (test 3) and 400 °C (test 4))

- In uniaxial compression tests conducted for Set-1, the average compressive strength of the reference specimens was measured as 21.85 MPa, while this value reached 63.78 MPa after applying GFRP to the specimens.
- Exposing the models of Set-2 to high temperatures has decreased their compressive strength. After exposing Test 3 specimens to Protocol-1 (200 °C), the compressive strength of the samples with no insulation reached 50.09 MPa and experienced the most strength loss. Exposing Test 4 specimens to Protocol-2 (400 °C) caused more decreases in their compressive strength. The strength of the model with no insulation had dropped significantly and reached 30.91 MPa.
- Similar to Set-1, the number of Dymatherm layers did not have a major effect on compressive strength of the insulated specimens.
- For the 400 °C exposure tests, the existence of RS material as an inner layer could decrease the compressive strength losses in the insulated specimens by 5%.

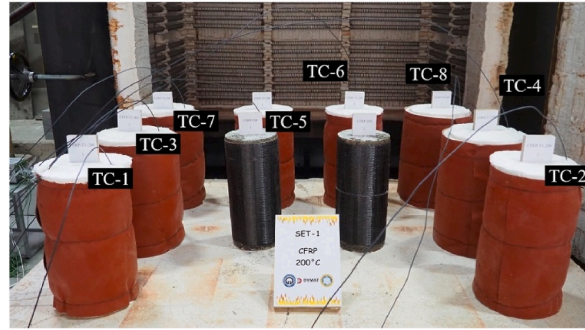
4. Conclusions

The performed experimental study has evaluated the performance of the recently developed fire protection system FIREWRAP for protecting the CFRP and GFRP wrapped concrete specimens. The effectiveness of the system was evaluated at different exposure temperatures of 200 °C and 400 °C. In addition, using different thicknesses in each configuration, the impacts of the thickness on high temperature performance of the system were evaluated. From the experiments performed, the following conclusions were drawn.

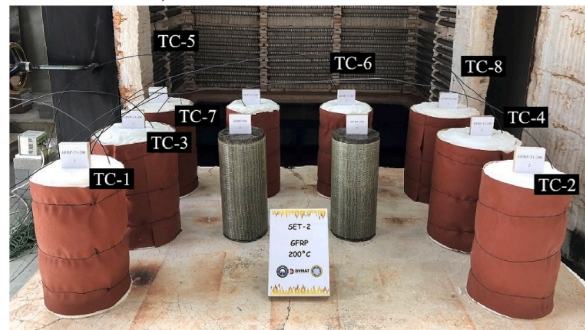
- The carbon fiber and glass fiber composites increased the compressive strength of the concrete specimens by 2.6 and 2.9 times, respectively.
- Exposing the non-insulated strengthened specimens to high temperatures of 200 °C and 400 °C decreased their compressive strength by 21% and 51%, respectively.
- The application of insulation could effectively decrease compressive strength losses. For CFRP strengthened specimens, thermal insulation has reduced the strength losses to 9% (for 200 °C tests) and 24% (for 400 °C tests). For GFRP strengthened specimens, after high temperature tests of 200 °C and 400 °C, the strength losses were reduced to 4% and 19%, respectively.
- Thermocouple readings demonstrated that during the high-temperature exposures of 200 °C and 400 °C, the utilized insulation could maintain the temperature of the FRPs between 30–55 °C and 50–125 °C, respectively.
- After 400 °C high-temperature tests, the residual strengths of the insulated specimens were similar to those of the non-insulated strengthened specimens after the 200 °C tests.
- From the visual observations after high temperature and compressive strength tests, it was observed that all the considered configurations could maintain the temperature of epoxy below its glass transition temperature and prevent its deterioration. For the specimens exposed to 200 °C, this effect was more prominent.
- Under a temperature exposure of 400 °C, all insulation configurations demonstrated satisfactory performance. However, reaching a final temperature of 50–125 °C at the end of the tests transformed the epoxy from a glassy to a rubbery state. This was more significant in the T1 and T2 specimens, which did not have an inner layer of RS material.
- The effectiveness of the insulation configurations was more evident for the CFRP-strengthened specimens. This confirms the higher sensitivity of CFRP to high temperatures than GFRP.
- Applying more layers of Dymatherm (4 layers) could decrease the temperature rises but did not have a significant effect on the compressive strength. Applying an inner layer of RS material can further improve this effect and reduce the strength losses.
- Although the inner layer of the RS material did not lead to a major improvement in the compressive strength losses (between 5 and 8%), it could effectively prevent the deterioration of the epoxy matrix and improve the thermal performance of the specimens.
- The results show that up to temperature exposure of 400 °C only 2 layers of Dymatherm can provide adequate thermal protection.
- Among the tested configurations, the specimens with an inner layer of RS outperformed the other specimens in terms of high temperature performance. The inner layer of RS material has importance due to the provided protection for the epoxy layer.



a) Test 1: Set-1 CFRP 400 °C



b) Test 2: Set-1 CFRP 200 °C



c) Test 3: Set-2 GFRP 200 °C



d) Test 4: Set-2 GFRP 400 °C

Fig. 10. Arrangement of the specimens and thermocouples.

However, considering the low impact of this layer on the compressive strength of the specimens, it can be substituted with a more cost-effective material with similar thermal properties.

- Considering the better high-temperature performance of the GFRP, the effectiveness of the insulation configurations within the considered temperature range could not be determined. Under a higher-temperature exposure, this thermal protection can be more pronounced, and results similar to those of CFRP-strengthened specimens can be obtained.

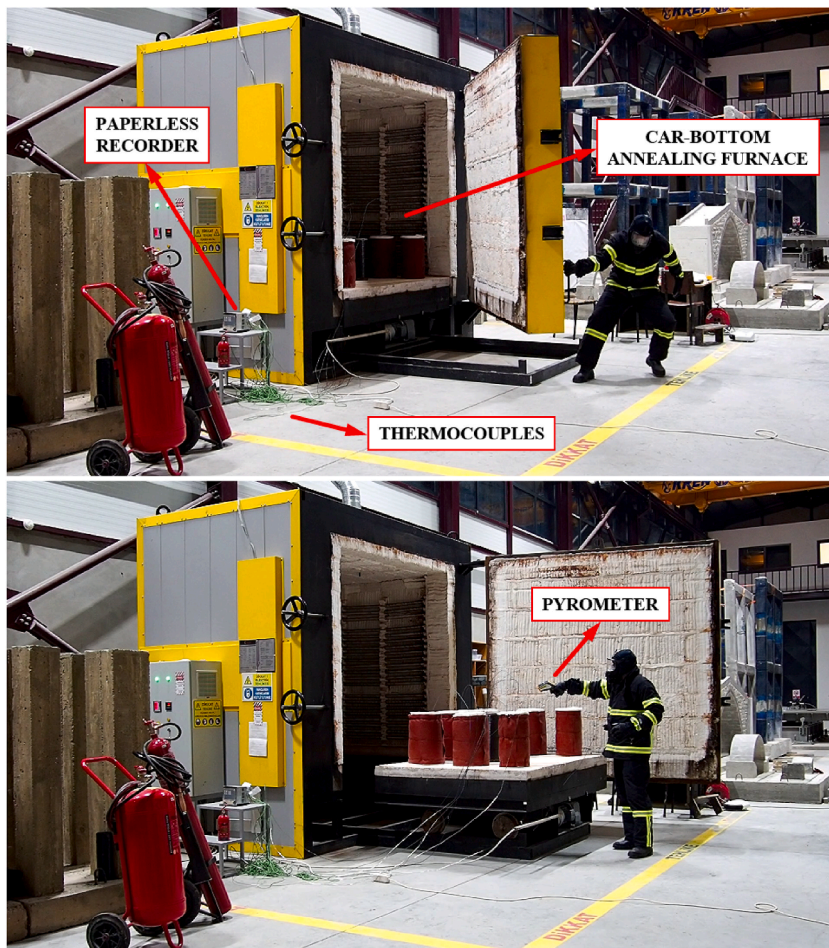
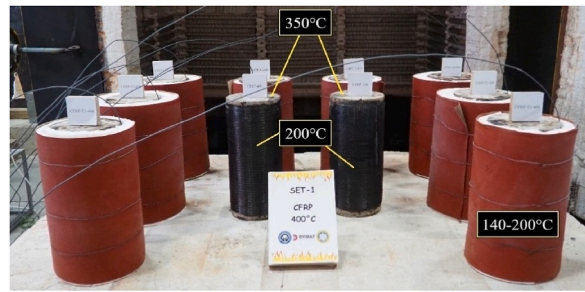


Fig. 11. Opening the furnace door and measuring the surface temperatures.

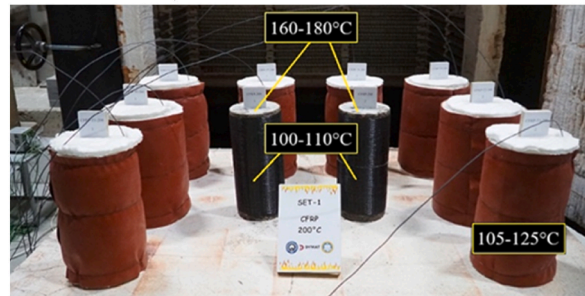


Fig. 12. Emission of smoke plume 400 °C tests.

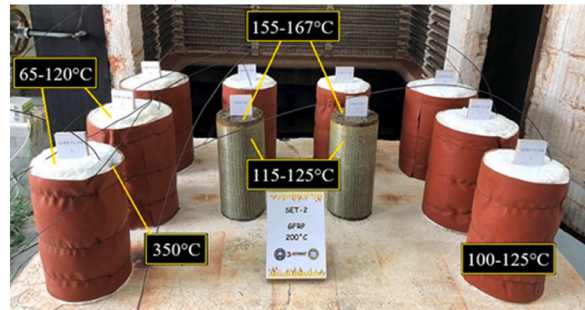
Overall, this study strengthens the widespread acceptance of FRP wrapping methods for enhancing the performance of structural elements and confirms the vulnerability of their physical and mechanical properties to high temperatures. The results of present study demonstrated that high temperatures can significantly degrade the structural performance of FRP-strengthened elements and it can take a role in initiating and spreading the fire. The test results highlighted the importance of implementing thermal insulation on FRP-wrapped concrete elements to decrease the possible structural and environmental damage caused by high-temperature exposure to FRP. The experimental results of this study demonstrated that the proposed insulation system reduced the strength losses of FRP to less than 25% under high temperatures, which is a significant improvement over non-insulated FRP specimens. However, broader research is required to evaluate the performance of the proposed insulation system on different structural elements and under the different fire conditions employed in previous studies. Additionally, the evaluations in this study were based on a limited number of specimens. Hence, to obtain a more comprehensive understanding of the performance of the system and draw a definitive conclusion, it is required to conduct additional analyses on a larger number of specimens.



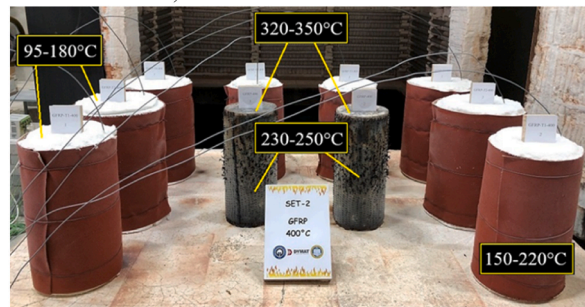
a) Test 1: Set-1 CFRP 400 °C



b) Test 2: Set-1 CFRP 200 °C



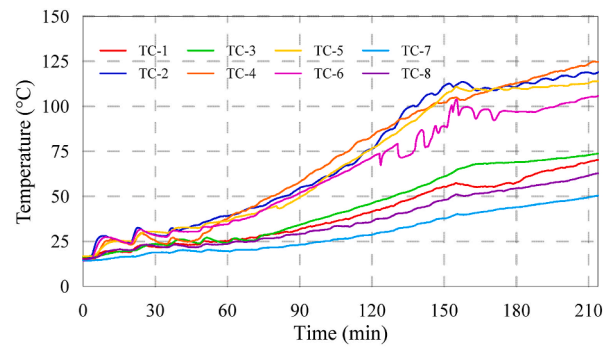
c) Test 3: Set-2 GFRP 200 °C



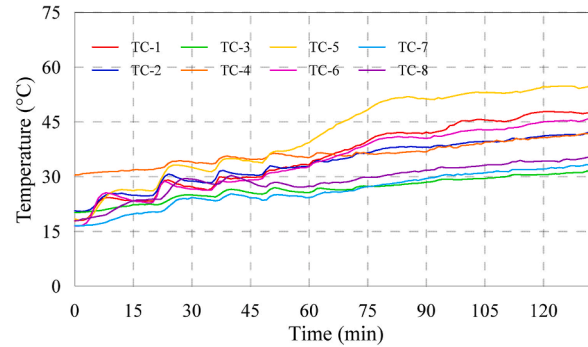
d) Test 4: Set-2 GFRP 400 °C

Fig. 13. Post-test condition of the specimens.

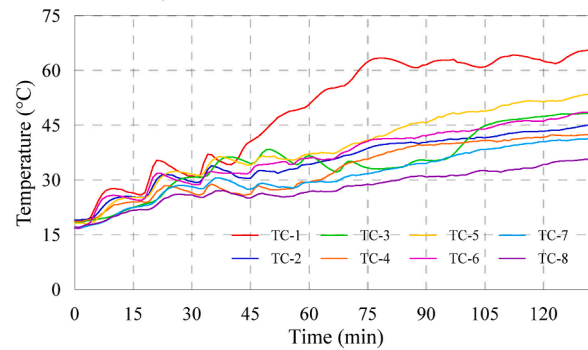
The tested fire protection comprised two durable sheets that are designed to withstand extreme weather conditions as well as high temperatures and fire. This makes it advantageous over paint and sprayed applied materials that are less durable. However, the major drawback of this system is its thickness. So, investigating the combination of DYMAT® RS, a very thin insulating material, with the other existing fire protection materials might lead to a more optimum solution. This system has good compatibility with steel structural members. So, it is suggested to perform a similar evaluation on high temperature performance of this system on steel members. Besides, to have a more comprehensive evaluation of the performance of this system, the performed investigation needs to be extended by evaluating the effects of different time-temperature curves with different heating rates and for different exposure durations.



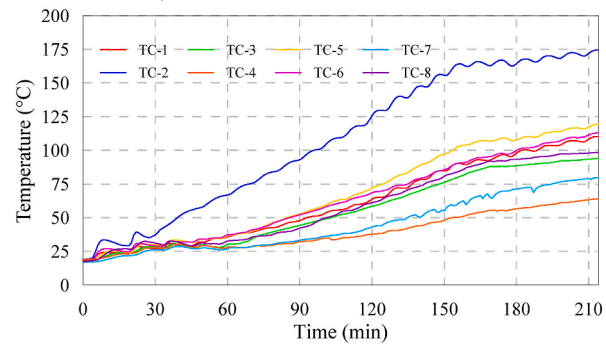
a) Test 1: Set-1 CFRP 400 °C



b) Test 2: Set-1 CFRP 200 °C



c) Test 3: Set-2 GFRP 200 °C



d) Test 4: Set-2 GFRP 400 °C

Fig. 14. Temperature variations of the FRPs during the temperature tests.

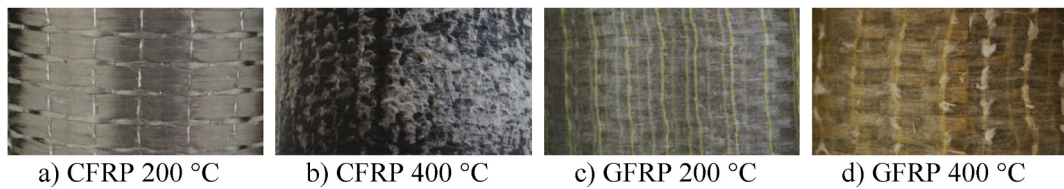


Fig. 15. Post temperature test condition of the insulated FRPs.

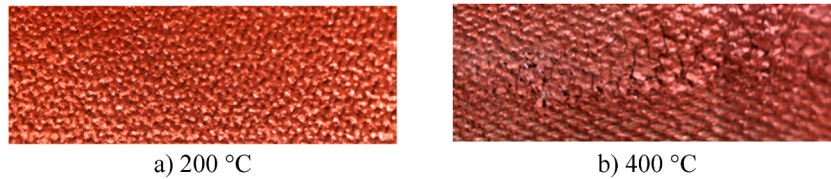


Fig. 16. Temperature exposure effect on RS material.

Table 6
Effectiveness of insulation types.

Comparing	Measurement Stations	Temperature differences between selected measurement stations at the end of the tests (°C)			
		Test 1	Test 2	Test 3	Test 4
T1-T3	1-5	44	7	11	9
	2-6	13	4	3	61
T2-T4	3-7	23	2	7	14
	4-8	62	6	7	34
T1-T2	1-3	3	16	17	16
	2-4	6	1	2	110
T3-T4	5-7	64	21	12	40
	6-8	43	11	13	14

Table 7
Comparison of compression test results for Set-1.

Specimen ID	No.	Height (mm)	Max. Load (N)	Max. Stress (N/mm ²)
Ref. Set-1	1	500	668591.38	21.28
Ref. Set-1	2	495	649674.38	20.68
Ref. Set-1	3	450	700831.81	22.31
CFRP	1	450	1756729.38	55.92
CFRP	2	450	1735335.88	55.24
CFRP-200	1	450	1289973.88	41.06
CFRP-200	2	450	1454258.50	46.29
CFRP-400	1	450	833603.38	26.53
CFRP-400	2	450	916042.94	29.16
CFRP-T1-200	1	450	–	–
CFRP-T1-200	2	450	1557017.88	49.56
CFRP-T1-400	1	450	1369665.63	43.60
CFRP-T1-400	2	450	1287087.50	40.97
CFRP-T2-200	1	450	1414657.88	45.03
CFRP-T2-200	2	450	1543619.50	49.13
CFRP-T2-400	1	450	1268892.00	40.39
CFRP-T2-400	2	450	1257975.88	40.04
CFRP-T3-200	1	450	1601409.75	50.97
CFRP-T3-200	2	450	1486868.38	47.33
CFRP-T3-400	1	450	1366398.38	43.49
CFRP-T3-400	2	450	1387070.25	44.15
CFRP-T4-200	1	450	1509295.13	48.04
CFRP-T4-200	2	450	1621360.13	51.61
CFRP-T4-400	1	450	–	–
CFRP-T4-400	2	450	1394817.25	44.40

Table 8

Comparison of compression test results for Set-2.

Specimen ID	No.	Height (mm)	Max. Load (N)	Max. Stress (N/mm ²)
Ref. Set-2	1	450	687895.25	21.90
Ref. Set-2	2	450	684841.50	21.80
GFRP	1	450	2005733.75	63.84
GFRP	2	450	2001496.63	63.71
GFRP	3	450	1671547.75	53.21
GFRP-200	1	450	1570035.25	49.98
GFRP-200	2	450	1577176.13	50.20
GFRP-400	1	450	971694.61	30.93
GFRP-400	2	450	970123.81	30.88
GFRP-T1-200	1	450	1862531.00	59.29
GFRP-T1-200	2	450	1963454.75	62.50
GFRP-T1-400	1	450	1605668.01	51.11
GFRP-T1-400	2	450	1668456.00	53.11
GFRP-T2-200	1	450	1855110.46	59.05
GFRP-T2-200	2	450	1906632.58	60.69
GFRP-T2-400	1	450	1620038.00	51.57
GFRP-T2-400	2	450	1690797.00	53.82
GFRP-T3-200	1	450	–	–
GFRP-T3-200	2	450	1942309.38	61.83
GFRP-T3-400	1	450	1540871.00	49.05
GFRP-T3-400	2	450	1594078.00	50.74
GFRP-T4-200	1	450	1946177.13	61.95
GFRP-T4-200	2	450	1997536.63	63.58
GFRP-T4-400	1	450	1592911.00	50.70
GFRP-T4-400	2	450	1693166.00	53.90

Table 9

Comparison of maximum temperatures and mechanical performance of specimens.

Test 1 CFRP 400 °C	Insulation Type	T1	T2	T3	T4
	Measurement Stations	1	2	3	4
	Max. Interface Temp. (°C)	70.32	119.06	73.74	124.88
	Strength	Final (MPa)	40.97	40.22	43.82
	Loss (%)	26.29	27.64	21.16	20.12
Test 2 CFRP 200 °C	Insulation Type	T1	T2	T3	T4
	Measurement Stations	1	2	3	4
	Max. Interface Temp. (°C)	48.23	42.29	31.89	41.79
	Strength	Final (MPa)	49.56	49.13	50.97
	Loss (%)	10.83	11.60	8.29	7.14
Test 3 GFRP 200 °C	Insulation Type	T1	T2	T3	T4
	Measurement Stations	1	2	3	4
	Max. Interface Temp. (°C)	65.53	45.38	48.45	42.89
	Strength	Final (MPa)	60.90	60.69	61.83
	Loss (%)	4.52	4.84	3.06	1.58
Test 4 GFRP 400 °C	Insulation Type	T1	T2	T3	T4
	Measurement Stations	1	2	3	4
	Max. Interface Temp. (°C)	110.17	174.50	94.07	63.98
	Strength	Final (MPa)	51.11	51.57	50.74
	Loss (%)	19.87	19.14	20.45	15.49

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

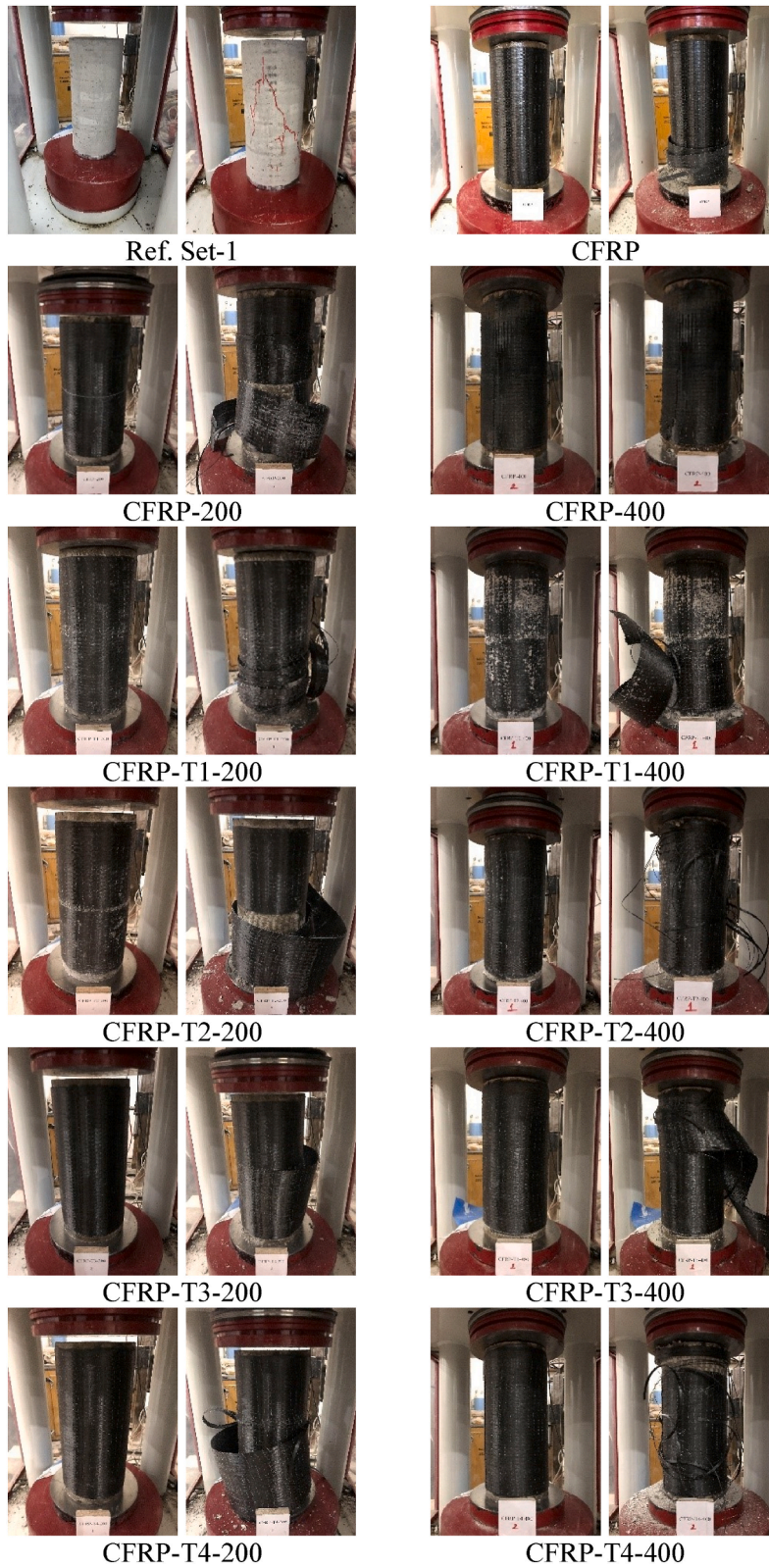


Fig. 17. Compression test of the Set-1 specimens.

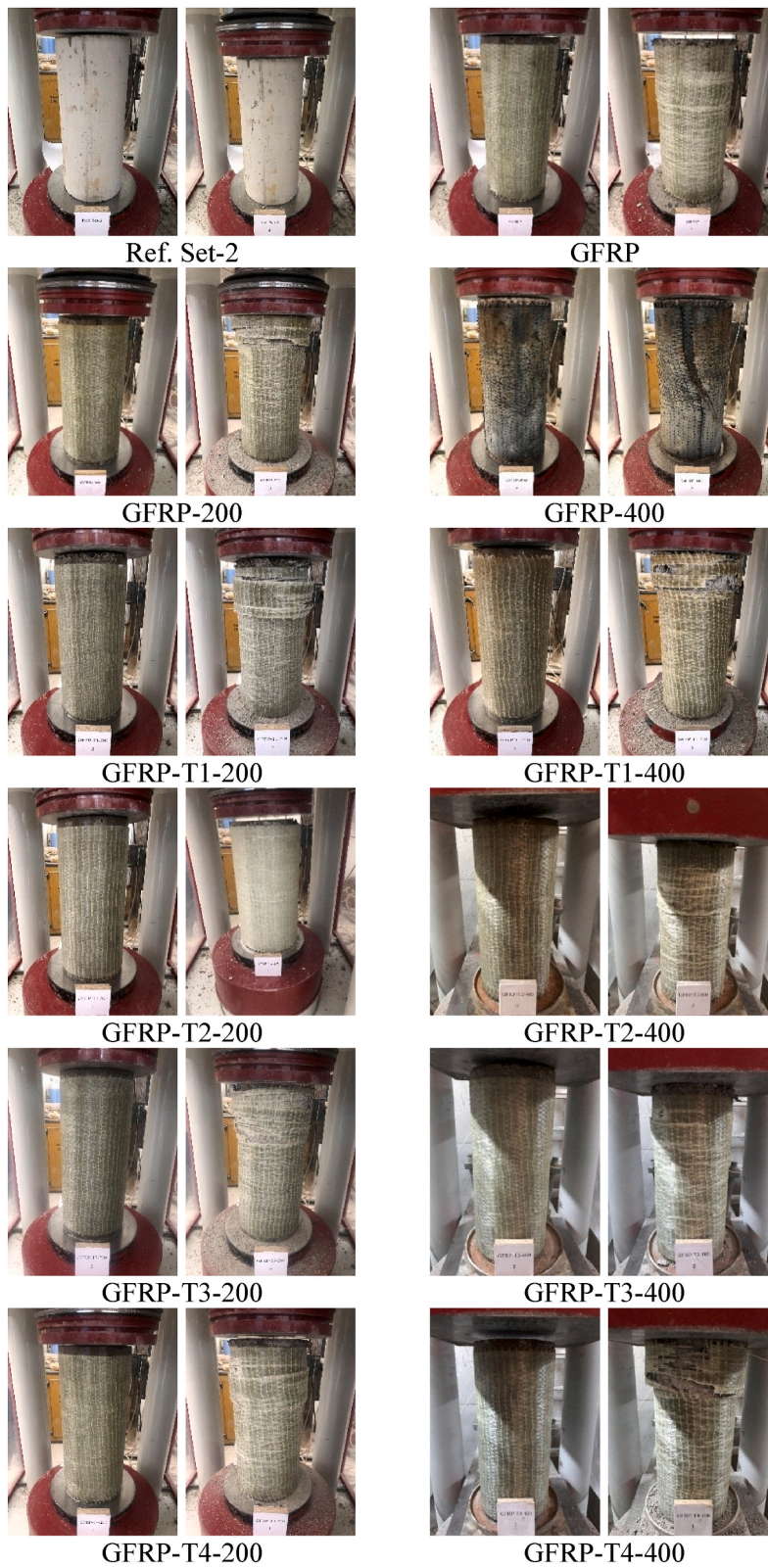


Fig. 18. Compression test of the Set-2 specimens.

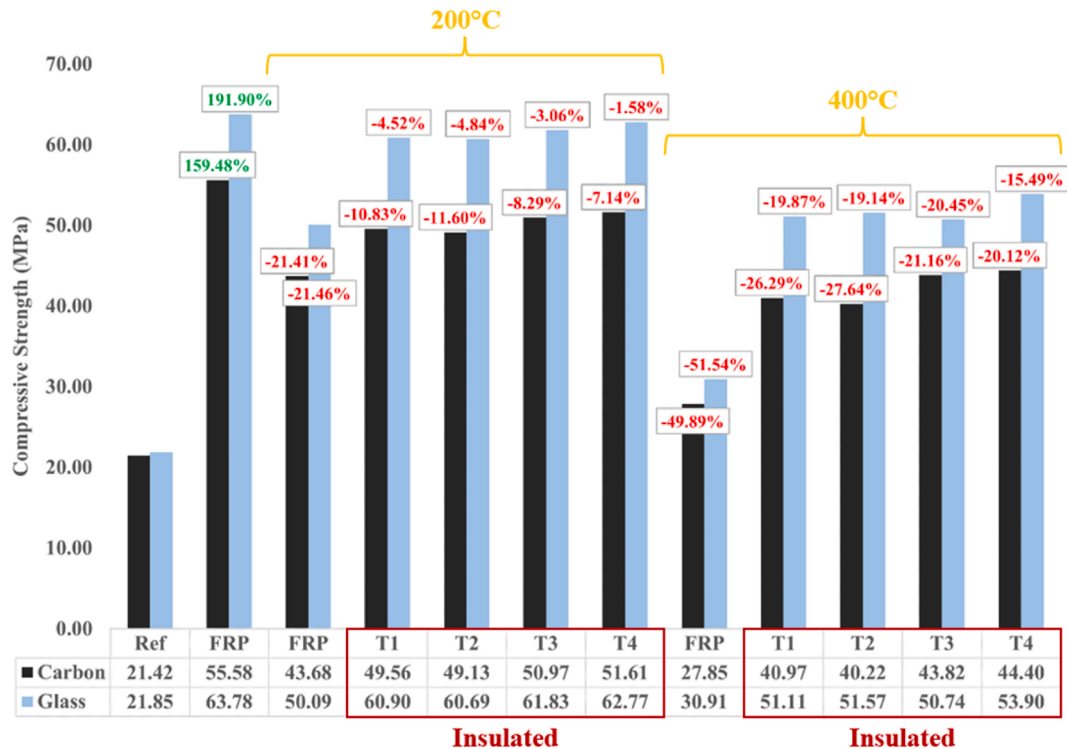


Fig. 19. Compressive strength of the tested specimens.

Data availability

Data will be made available on request.

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References

- [1] M.H. Lai, Y.W. Liang, Q. Wang, F.M. Ren, M.T. Chen, J.C.M. Ho, A stress-path dependent stress-strain model for FRP-confined concrete, *Eng. Struct.* 203 (2020), <https://doi.org/10.1016/j.engstruct.2019.109824>.
- [2] J. Song, W.Y. Gao, L.J. Ouyang, J.J. Zeng, J. Yang, W.D. Liu, Compressive behavior of heat-damaged square concrete prisms confined with basalt fiber-reinforced polymer jackets, *Eng. Struct.* 242 (2021), <https://doi.org/10.1016/j.engstruct.2021.112504>.
- [3] L.J. Ouyang, X.X. Wei, B. Ding, W.Y. Gao, Effective strain of BFRP for confined heat-damaged concrete cylinders, *Front. Mater.* 8 (2021), <https://doi.org/10.3389/fmats.2021.729781>.
- [4] P.L. Nguyen, X.H. Vu, E. Ferrier, Elevated temperature behaviour of carbon fibre-reinforced polymer applied by hand lay-up (M-CFRP) under simultaneous thermal and mechanical loadings: experimental and analytical investigation, *Fire Saf. J.* 100 (2018) 103–117, <https://doi.org/10.1016/j.firesaf.2018.07.007>.
- [5] A. Zaman, S.A. Gutub, M.A. Wafa, A review on FRP composites applications and durability concerns in the construction sector, *J. Reinforc. Plast. Compos.* 32 (24) (2013) 1966–1988, <https://doi.org/10.1177/0731684413492868>.
- [6] Y.Y. Ye, Y. Zhuge, S.T. Smith, J.J. Zeng, Y.L. Bai, Behavior of GFRP-RC columns under axial compression: assessment of existing models and a new axial load-strain model, *J. Build. Eng.* 47 (2022), <https://doi.org/10.1016/j.jobte.2021.103782>.
- [7] Y.Y. Ye, J.J. Zeng, P.L. Li, A state-of-the-art review of FRP-confined steel-reinforced concrete (FCSRC) structural members, *Polymers* 14 (4) (2022) 677, <https://doi.org/10.3390/polym14040677>.
- [8] C. Burgoyne, I. Balafas, Why is FRP not a financial success? in: *Proceedings of the 8th International Symposium on Fiber Reinforced Polymer Reinforcement for Reinforced Concrete Structures (FRPRCS-8)*, 2007, pp. 1–10. <http://www-civ.eng.cam.ac.uk/cjb/papers/cp74.pdf>.
- [9] P. Ilg, C. Hoehne, E. Guenther, High-performance materials in infrastructure: a review of applied life cycle costing and its drivers - the case of fiber-reinforced composites, *J. Clean. Prod.* 112 (2016) 926–945, <https://doi.org/10.1016/j.jclepro.2015.07.051>.
- [10] A.Q. Sobia, H. Afifudin, M.S. Hamidah, I. Azmi, Thermo-mechanical behavior of fire insulated fiber-reinforced polymer (FRP) strengthened reinforced concrete square column, *Asian J. Civil Eng.* 23 (4) (2022) 573–583, <https://doi.org/10.1007/s42107-022-00442-y>.
- [11] G. Xian, R. Guo, C. Li, Y. Wang, Mechanical performance evolution and life prediction of prestressed CFRP plate exposed to hygrothermal and freeze-thaw environments, *Compos. Struct.* 293 (2022) 115719, <https://doi.org/10.1016/j.compstruct.2022.115719>.
- [12] N. Taniguchi, T. Nishiwaki, H. Kawada, Tensile strength of unidirectional CFRP laminate under high strain rate, *Advanced Composite Materials*, Off. J. Jap. Soc. Compos. Mater. 16 (2) (2007) 167–180, <https://doi.org/10.1163/156855107780918937>.
- [13] C. Ding, R. Wang, Experimental investigation of thermal contact conductance across GFRP–GFRP joint, *Heat Mass Tran.* 51 (3) (2015) 433–439, <https://doi.org/10.1007/s00231-014-1425-y>.
- [14] B. Su, J. Chen, J. Hao, X. Fan, X. Han, Thermal insulation performance of GFRP squared tube reinforced sandwich panel, *Energy Build.* 211 (2020), <https://doi.org/10.1016/j.enbuild.2020.109790>.

- [15] A. Mosallam, F. Abdi, Z. Qian, Fire resistance simulation of loaded deck sandwich panel and deck-bulkhead assembly structures, *Compos. B Eng.* 39 (1) (2008) 191–195, <https://doi.org/10.1016/j.compositesb.2007.02.022>.
- [16] K. Protchenko, E. Szmigiera, Post-Fire characteristics of concrete beams reinforced with hybrid FRP bars, *Materials* 13 (5) (2020), <https://doi.org/10.3390/ma13051248>.
- [17] T.B. Carlos, J.P.C. Rodrigues, R.C.A. de Lima, D. Dhima, Experimental analysis on flexural behaviour of RC beams strengthened with CFRP laminates and under fire conditions, *Compos. Struct.* 189 (2018) 516–528, <https://doi.org/10.1016/j.compstruct.2018.01.094>.
- [18] A.P. Mouritz, A.G. Gibson, *Fire Properties of Polymer Composite Materials*, vol. 143, Springer Science & Business Media, 2006, <https://doi.org/10.1007/978-1-4020-5356-6>.
- [19] B. Schartel, J.K. Humphrey, A.G. Gibson, A. Hörold, V. Trappe, V. Gettwert, Assessing the structural integrity of carbon-fibre sandwich panels in fire: bench-scale approach, *Compos. B Eng.* 164 (2019) 82–89, <https://doi.org/10.1016/j.compositesb.2018.11.077>.
- [20] A. Katz, N. Berman, Modeling the effect of high temperature on the bond of FRP reinforcing bars to concrete, *Cement Concr. Compos.* 22 (6) (2000) 433–443, [https://doi.org/10.1016/S0958-9465\(00\)00043-3](https://doi.org/10.1016/S0958-9465(00)00043-3).
- [21] A. Bilotta, A. Compagnone, L. Esposito, E. Nigro, Structural behaviour of FRP reinforced concrete slabs in fire, *Eng. Struct.* 221 (2020), <https://doi.org/10.1016/j.engstruct.2020.111058>.
- [22] Z. Huang, The behaviour of reinforced concrete slabs in fire, *Fire Saf. J.* 45 (5) (2010) 271–282, <https://doi.org/10.1016/j.firesaf.2010.05.001>.
- [23] Y. Bai, T. Vallée, T. Keller, Modeling of thermal responses for FRP composites under elevated and high temperatures, *Compos. Sci. Technol.* 68 (1) (2008) 47–56, <https://doi.org/10.1016/j.compscitech.2007.05.039>.
- [24] V.K.R. Kodur, P.P. Bhatt, A numerical approach for modeling response of fiber reinforced polymer strengthened concrete slabs exposed to fire, *Compos. Struct.* 187 (2018) 226–240, <https://doi.org/10.1016/j.compstruct.2017.12.051>.
- [25] W.Y. Gao, J.G. Teng, J.-G. Dai, Effect of temperature variation on the full-range behavior of FRP-to-concrete bonded joints, *J. Compos. Construct.* 16 (6) (2012) 671–683, [https://doi.org/10.1061/\(asce\)cc.1943-5614.0000296](https://doi.org/10.1061/(asce)cc.1943-5614.0000296).
- [26] J. Kumar, R. Bajpai, Performance of FRP confined concrete columns in fire, *Int. J. Adv. Technol. Civil Eng.* 1 (2) (2012) 102–105, <https://doi.org/10.47893/ijatce.2012.1014>.
- [27] J.-G. Dai, W.Y. Gao, J.G. Teng, Bond-slip model for FRP laminates externally bonded to concrete at elevated temperature, *J. Compos. Construct.* 17 (2) (2013) 217–228, [https://doi.org/10.1061/\(asce\)cc.1943-5614.0000337](https://doi.org/10.1061/(asce)cc.1943-5614.0000337).
- [28] D. Guo, W.Y. Gao, D. Fernando, J.G. Dai, Effect of temperature variation on the plate-end debonding of FRP-strengthened beams: a theoretical study, *Adv. Struct. Eng.* 25 (2) (2022) 290–305, <https://doi.org/10.1177/13694332211046342>.
- [29] H. Hajiloo, M.F. Green, GFRP reinforced concrete slabs in fire: finite element modelling, *Eng. Struct.* 183 (2019) 1109–1120, <https://doi.org/10.1016/j.engstruct.2019.01.028>.
- [30] V.K.R. Kodur, A. Ahmed, Numerical model for tracing the response of FRP-strengthened RC beams exposed to fire, *J. Compos. Construct.* 14 (6) (2010) 730–742, [https://doi.org/10.1061/\(asce\)cc.1943-5614.0000129](https://doi.org/10.1061/(asce)cc.1943-5614.0000129).
- [31] D. Duan, L. Ouyang, W. Gao, Q. Xu, W. Liu, J. Yang, Fire performance of FRP-RC flexural members: a numerical study, *Polymers* 14 (2) (2022), <https://doi.org/10.3390/polym14020346>.
- [32] M. Adelzadeh, H. Hajiloo, M.F. Green, Numerical study of FRP reinforced concrete slabs at elevated temperature, *Polymers* 6 (1) (2014) 408–422, <https://doi.org/10.3390/polym6020408>.
- [33] W.Y. Gao, J.G. Dai, J.G. Teng, Fire resistance design of un-protected FRP-strengthened RC beams, *Mater. Struct.* 49 (12) (2016) 5357–5371, <https://doi.org/10.1617/s11527-016-0865-x>.
- [34] S.W. Yoo, J.F. Choo, Behavior of CFRP-reinforced concrete columns at elevated temperatures, *Construct. Build. Mater.* 358 (2022) 129425, <https://doi.org/10.1016/j.conbuildmat.2022.129425>.
- [35] Y.A. Al-Salloum, H.M. Elsanadedy, A.A. Abadel, Behavior of FRP-confined concrete after high temperature exposure, *Construct. Build. Mater.* 25 (2) (2011) 838–850, <https://doi.org/10.1016/j.conbuildmat.2010.06.103>.
- [36] E. Nigro, G. Cefarelli, A. Bilotta, G. Manfredi, E. Cosenza, Behavior of FRP reinforced concrete slabs in case of fire: theoretical models and experimental tests, *Adv. Struct. Eng.* 15 (4) (2012) 637–652, <https://doi.org/10.1260/1369-4332.15.4.637>.
- [37] V.V. Cao, H.B. Vo, L.H. Dinh, D.V. Doan, Experimental behavior of fire-exposed reinforced concrete slabs without and with FRP retrofitting, *J. Build. Eng.* 51 (2022), <https://doi.org/10.1016/j.jobbe.2022.104315>.
- [38] M. Bazli, M. Abolfazli, Mechanical properties of fibre reinforced polymers under elevated temperatures: an overview, *Polymers* 12 (11) (2020), <https://doi.org/10.3390/polym12112600>.
- [39] Y.S.S. Al-Kamaki, R. Al-Mahaidi, I. Bennetts, An experimental investigation of the behaviour of heat-damaged RC columns confined with CFRP fabrics using photogrammetry, *Mater. Struct.* 50 (1) (2017), <https://doi.org/10.1617/s11527-016-0873-x>.
- [40] Y.S.S. Al-Kamaki, R. Al-Mahaidi, I. Bennetts, Experimental and numerical study of the behaviour of heat-damaged RC circular columns confined with CFRP fabric, *Compos. Struct.* 133 (2015) 679–690, <https://doi.org/10.1016/j.compstruct.2015.07.116>.
- [41] R.J.A. Hamad, M.A. Megat Johari, R.H. Haddad, Effects of bars slippage on the pre-and post-heating flexural behavior of FRP reinforced concrete beams: experimental and theoretical investigations, *Int. J. Civ. Eng. Technol.* 10 (2) (2019) 574–602.
- [42] H. Blontrock, L. Taerwe, P. Vandeveld, Fire tests on concrete beams strengthened with fibre composite laminates, in: Konrad Bergmeister (Ed.), *Proceedings of the International PhD Symposium in Civil Engineering, Vienna (Austria), 5-7 October 2000*, vol. 2, 2000, pp. 151–161. <http://hdl.handle.net/1854/LU-130382>.
- [43] R. Barnes, J. Fidell, Performance in fire of small-scale CFRP strengthened concrete beams, *J. Compos. Construct.* 10 (6) (2006) 503–508, [https://doi.org/10.1061/\(asce\)1090-0268\(2006\)10:6\(503\)](https://doi.org/10.1061/(asce)1090-0268(2006)10:6(503)).
- [44] A. Ahmed, V. Kodur, The experimental behavior of FRP-strengthened RC beams subjected to design fire exposure, *Eng. Struct.* 33 (7) (2011) 2201–2211, <https://doi.org/10.1016/j.engstruct.2011.03.010>.
- [45] A. Palmieri, S. Matthys, L. Taerwe, Experimental investigation on fire endurance of insulated concrete beams strengthened with near surface mounted FRP bar reinforcement, *Compos. B Eng.* 43 (3) (2012) 885–895, <https://doi.org/10.1016/j.compositesb.2011.11.061>.
- [46] G. Ji, G. Li, W. Alaywan, A new fire resistant FRP for externally bonded concrete repair, *Construct. Build. Mater.* 42 (2013) 87–96, <https://doi.org/10.1016/j.conbuildmat.2013.01.008>.
- [47] B. Yu, V.K.R. Kodur, Fire behavior of concrete T-beams strengthened with near-surface mounted FRP reinforcement, *Eng. Struct.* 80 (2014) 350–361, <https://doi.org/10.1016/j.engstruct.2014.09.003>.
- [48] S.Y. Seo, J.W. Lim, S.H. Jeong, Evaluation on the bond capacity of the fire-protected FRP bonded to concrete under high temperature, *Int. J. Concr. Struct. Mater.* 15 (2021) 1–24, <https://doi.org/10.1186/s40069-020-00448-3>.
- [49] Y.K. Guruprasad, A. Ramaswamy, Thermal insulation of concrete and the repair material CFRP exposed to high temperature and different time intervals, *Construct. Build. Mater.* 205 (2019) 549–565, <https://doi.org/10.1016/j.conbuildmat.2019.01.236>.
- [50] M. Imran, M. Mahendran, Fire behaviour of CFRP strengthened short SHS steel columns with and without insulation, *Compos. B Eng.* 193 (2020), <https://doi.org/10.1016/j.compositesb.2020.108016>.
- [51] V.K.R. Kodur, P.P. Bhatt, M.Z. Naser, High temperature properties of fiber reinforced polymers and fire insulation for fire resistance modeling of strengthened concrete structures, *Compos. B Eng.* 175 (2019), <https://doi.org/10.1016/j.compositesb.2019.107104>.
- [52] A. Selvaratnam, J.C.P.H. Gamage, A review on thermo-mechanical behaviour of CFRP-concrete composites at elevated temperature and available insulation systems, *Lect. Notes Civ. Eng.* 94 (2021) 533–541, https://doi.org/10.1007/978-981-15-7222-7_43.
- [53] H. Elsanadedy, T. Almusallam, Y. Al-Salloum, R. Iqbal, Effect of high temperature on structural response of reinforced concrete circular columns strengthened with fiber reinforced polymer composites, *J. Compos. Mater.* 51 (3) (2017) 333–355, <https://doi.org/10.1177/0021998316645171>.
- [54] M. Usman, M. Yaqub, M. Auzair, W. Khaliq, M. Noman, A. Afaq, Restorability of strength and stiffness of fire damaged concrete using various composite confinement techniques, *Construct. Build. Mater.* 272 (2021), <https://doi.org/10.1016/j.conbuildmat.2020.121984>.

- [55] BS EN 206:2013, Concrete – Specification, Performance, Production and Conformity, British Standards Institution (BSI), London, 2013.
- [56] C.S. Poon, S. Azhar, M. Anson, Y.L. Wong, Performance of metakaolin concrete at elevated temperatures, *Cement Concr. Compos.* 25 (1) (2003) 83–89, [https://doi.org/10.1016/S0958-9465\(01\)00061-0](https://doi.org/10.1016/S0958-9465(01)00061-0).
- [57] B. Demirel, O. Keleştemur, Effect of elevated temperature on the mechanical properties of concrete produced with finely ground pumice and silica fume, *Fire Saf. J.* 45 (6–8) (2010) 385–391, <https://doi.org/10.1016/j.firesaf.2010.08.002>.
- [58] A.H. Akca, N.Ö. Zihnioğlu, High performance concrete under elevated temperatures, *Construct. Build. Mater.* 44 (2013) 317–328, <https://doi.org/10.1016/j.conbuildmat.2013.03.005>.
- [59] M.W. Hussin, M.A.R. Bhutta, M. Azreen, P.J. Ramadhansyah, J. Mirza, Performance of blended ash geopolymer concrete at elevated temperatures, *Mater. Struct.* 48 (3) (2015) 709–720, <https://doi.org/10.1617/s11527-014-0251-5>.
- [60] Y. Esen, A. Kurt, Effect of high temperature in concrete for different mineral additives and rates, *KSCE J. Civ. Eng.* 22 (4) (2018) 1288–1294, <https://doi.org/10.1007/s12205-017-1224-3>.
- [61] M. Malik, S.K. Bhattacharyya, S.V. Barai, Thermal and Mechanical Properties of Concrete and its Constituents at Elevated Temperatures: A Review, *Construction and Building Materials*, Elsevier Ltd, 2021, <https://doi.org/10.1016/j.conbuildmat.2020.121398>.
- [62] BS EN 12390-2:2009, Testing Hardened Concrete - Part 2: Making and Curing Specimens for Strength Tests, British Standards Institution (BSI), 2009.
- [63] BS EN 12390-3:2009, Testing Hardened Concrete - Part 3: Compression Strength of Test Specimens, British Standards Institution (BSI), 2009.
- [64] A.P. Mouritz, A.G. Gibson, Fire Properties of Polymer Composite Materials, Springer Netherlands, 2006, <https://doi.org/10.1007/978-1-4020-5356-6>.